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Atlantic Research Corporation

TECHNICAL REPORT AFML-TR-65-315,PART II

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Air Force Materials Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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AFML-TR-65-315,PART II

ABLATIVE PLASTIC CHARACTERIZATION IN SOLID PROPELLANT EXHAUST

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FOREWORD

This report was prepared by J. D. Batchelor of Atlantic Research Corporation, Henry G. Shirley Memorial Highway at Edsall Road, Alexandria, Virginia under USAF Contract No. AF 33(615)-1631. This contract was initiated under Project No. 7340, "Nonmetallic and Composite Materials," Task No. 734001, "Thermally Protective Pastics and Composites." The work was administered under the direction of the Nonmetallic Materials Division, AF Materials Laboratory, Research and Technology Division, with Mr. Paul F. Pirrung as project engineer.

This report covers work accomplished from 1 July 1965 to 31 January 1967.

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This technical report has been reviewed and is approved.

R. G. SPAIN, Acting Chief
Plastics and Composites Branch
Nonmetallic Materials Division
Air Force Materials Laboratory

ABSTRACT

The purpose of this program was to characterize ablative plastics for service in the nozzle region of solid propellant motors. Evaluation of specimens provided by the Air Force Materials Laboratory was accomplished by exposure to a realistic chemical, mechanical, and thermal environment in a subscale, high-velocity motor test. This report describes the work of the final nineteen months of a thirty-two month program. The standard test method developed in the previous year (AFML-TR-65-315) was used for thirteen firing tests. Based on the first two of these firings, flat laminate specimens were chosen as standard because char rate data could be obtained and specimen fabrication was greatly simplified. Four replicate specimens of each composition were used to provide reliable data. In the final eleven firing tests, seventeen different resins or resin mixtures were compared with a standard commercial phenolic with either graphite or carbon cloth reinforcement. Two resins (naphthalene diol and phenylphenol phenol formaldehyde) gave significantly better results than the standard. Several other resins, including a chrome phenolic, polyphenyl, polyimide, and 2-7 dihydroxy-naphthalene phenol formaldehyde, showed either similar performance or promise for improved performance.

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1.0 INTRODUCTION

Ablative plastic materials are commonly used in solid propellant rocket motors to protect the structural parts of the motor from the hot combustion products of the propellant. The efficiency and reliability with which available ablative plastics perform this function is a significant factor in the performance that may be achieved in a rocket motor. For this reason the Air Force has maintained a continuing interest and support of research and development work on ablative plastic composites.

The Plastics and Composites Branch, Nonmetallic Materials Division, Air Force Materials Laboratory has supported a continuing effort to develop improved resins and reinforcements for use in ablative composites. A necessary phase of such a research program is the characterization of ablative compositions under realistic service conditions. The behavior of candidate ablative plastics must be studied to indicate fruitful areas for further materials research and to measure the degree of success in the preparation of superior materials. The program described in this report is a part of this characterization effort.

In the region of the nozzle of a solid propellant rocket motor ablative plastics are used to insulate the aft closure and maintain the nozzle entrance contour, to support and insulate the nozzle throat insert, and to serve as an expansion cone to achieve maximum thrust. In some motors the nozzle throat insert may be fabricated from an ablative plastic composite. The conditions which are typical of each of these locations vary in many respects, but they do share in common severe factors such as high heat flux and highly erosive flow conditions.

The testing and characterization of materials under conditions typical of areas near the nozzle, such as aft closure insulation and nozzle entrance sections, are the objectives of the current program. In subscale rocket motors of conventional design the area near the nozzle is not large enough to provide space for materials evaluation specimens. Therefore, a special motor test technique developed at Atlantic Research Corporation in prior work was selected for adaptation to the needs of the current program. In this test a high velocity test section mounted between the motor chamber and the nozzle is used to expose specimens to the desired chemical, thermal, and mechanical environment.

This report describes the final nineteen months' effort on a thirty-two month program to characterize and compare ablative plastic materials, supplied by the Air Force Materials Laboratory, through the use of a standardized motor exposure of the type described above. The principal effort during the first year was to adapt the test conditions to meet the Air Force requirements and to characterize the standard test. During the period of this report this standard test method was used to study the response of a total of 156 specimens in 13 firings.

2.0 SUMMARY

The test method developed and standardized in the first year of this program provided a means of exposing twelve flat panel specimens simultaneously to the erosive action of a hot combustion gas flow at about Mach 0.25 conditions at 500 psi. This test configuration, which provides a cold wall heat flux of 770 Btu/sq ft, sec, was used first to select a preferred standard reinforcement orientation for test specimens and then to compare a wide variety of developmental resin binders. The reproducibility of the firing conditions was good in each test.

In the first two of the thirteen firing tests covered by this report the relative behavior of flat laminates, edge-oriented laminates, and chopped cloth square reinforcements were examined. The decision was made to use flat laminate construction for the remainder of the experimental specimens. This decision was made because char rate data could only be obtained when the reinforcement orientation was parallel to the heated surface of the specimen and because the flat laminate specimens were much simpler and less costly to prepare as input to this program. The disadvantage associated with the flat laminates was the delamination tendency which introduced a need for experienced judgment in the reduction of the test data. Based on the data from the eleven firing tests made for materials comparison, it was concluded that (1) delamination was an inherent problem with parallel laminate specimens, but (2) the extent of delamination was likely affected by the quality of the interlaminar bonding achieved in the preparation of the test specimens by laboratory methods.

Both graphite cloth and carbon cloth were used as reinforcements. A standard commercial phenolic resin showed similar erosion rates with either reinforcement; the average char rate of the phenolic/graphite cloth was somewhat higher than for the phenolic/carbon cloth as would be expected. In a few instances the degradation rates of the standard control materials were abnormal even though no abnormality was evident in the observed firing conditions. It was concluded that the primary materials comparisons should be based on the control data obtained in the same firing in which the experimental specimens were tested.

The data obtained on a rather wide range of resins of the type which exhibit high thermal stability showed that it is not easy to improve on the standard commercial phenolic resin for the service conditions used. Only two resins showed rather clearly superior performance; these were the naphthalene diol and a phenyl-phenol phenol formaldehyde system. Several other resins, in particular chrome phenolic, polyphenyl, polyimide, and 2-7 dihydroxynaphthalene phenol formaldehyde, showed promise. The only resin which was found completely unsuited for the highly erosive test environment was the polyphenylene oxide, a high temperature thermoplastic material.

3.0 ROCKET MOTOR TEST METHOD

The evaluation technique used in this program consisted of subscale rocket motor firing tests. The chemical environment in such tests is determined by the propellant formulation used. The configuration of the motor hardware largely determines the mechanical environment and the thermal environment is determined both by the propellant and the configuration of the specimens in the rocket motor. During the first year a standard motor test method which provided the proper combination of chemical, mechanical, and thermal conditions for the evaluation of erosion-resistant materials was selected and characterized. This work which was closely coordinated with the Air Force Project Engineer is fully documented in AFML-TR-65-315. The propellant and test configuration which were used in the standard test are briefly described in the following sections. A description of the procedures used to inspect the specimens after test to determine their behavior is also given.

A. PROPELLANT DESCRIPTION

The propellant selected was a conventional aluminized solid propellant designated Arcadene 127-A. This particular propellant was chosen by the Air Force Project Engineer because its combustion products are typical of propellants of primary interest to the Air Force. The pertinent characteristics of Arcadene 127-A are listed in Table I. The flame temperature of this propellant is moderate (5700°F at 500 psia), but the combustion products are quite oxidizing.

B. TEST CONFIGURATION

The basic configuration used in this program was a high velocity motor test developed in previous work at Atlantic Research. The details of the configuration, such as the specimen mounting, the bore within the test section, and the nozzle throat diameter, were varied during the first year's work to achieve the desired test severity, but the basic configuration remained unchanged.

The test hardware consisted of three distinct parts; the motor tube, the specimen test section, and the nozzle assembly. The motor tube was a heavy walled cylinder 13 inches in diameter in which the propellant burns. The test section consisted of a motor closure with a blast tube extension in which the specimens to be evaluated were mounted. The nozzle assembly was flanged to the upper end of the blast tube. An assembly view of the complete motor test unit is shown in Figure 1.

One of the chief advantages of the high velocity motor test procedure is the capability to test multiple specimens of simple flat panel shape in a single firing. The specimens were mounted in the test section to form a square bore. The total useable length in the blast tube was 10 inches; three test sections 3-1/2 inches long, each containing four specimens, were placed end to end in the blast tube to achieve a capacity of twelve specimens in each test firing. The gas velocity in the test section is determined by the ratio of the cross section of the square bore formed by the specimens to the area of the nozzle throat. Increasing the gas velocity through the test section increases the erosive severity of the test environment. The nominal conditions utilized in each test reported herein were as follows:

Motor Pressure - 500 psi

Duration - 30 seconds

Area Ratio in Test Section - 3.1 (initial value)

As reported in AFML-TR-65-315, the measured average heat flux to a copper heat-sink calorimeter was 770 Btu/sq ft, sec for this test configuration.

The standard specimen mounting configuration is shown in Figure 2. The entire support piece consisted of a die-molded section of epoxy-asbestos material. Four specimens were bonded with an epoxy cement into the shaped recesses molded into the support pieces. These support pieces were molded to accept specimens two inches wide; if specimens were narrower, their width was first built up to two inches by bonding plastic shim strips to each side of the specimen. Three support pieces with four specimens each and totalling ten inches in length were inserted end to end into the steel tube of the test section for motor test. This mounting procedure proved entirely satisfactory in all firings. In firing ASD-16 and all subsequent tests a gap filled with a flexible resin was left at each bevelled corner to provide an edgewise expansion joint in the hope of reducing specimen delamination. This practice appeared to make no difference, either for better or worse.

To achieve reliable and reproducible performance a tungsten nozzle insert was selected. The nozzle assembly consisted of a steel housing, carbon insulating pieces, and an entrance and expansion cone of graphite along with the tungsten throat insert. With this design a neutral pressure trace and excellent reproducibility was achieved and the throat insert could be used repetitively.

C. POST FIRING ANALYSIS

After test each specimen was examined to characterize its behavior. Each test section, consisting of four test specimens and the associated support piece, was cut in half, normal to the axis of the section, to expose the specimen thickness at the center of its length. The cut edge was cleaned by light sanding so that the heat affected zone could be distinguished. The principal data consisted of measurements of the post-test total thickness, char thickness, and uncharred material thickness. The average erosion rate and average char rate were defined as follows:

$$\text{Erosion rate, mil/sec} = \frac{\text{(Original thickness--Final thickness)}}{\text{Firing duration}}$$

$$\text{Char rate, mil/sec} = \frac{\text{(Original thickness--Final uncharred thickness)}}{\text{Firing duration}}$$

4.0 RESULTS

During the period of this report a total of thirteen motor firing tests were carried out. In each firing test twelve individual flat panel specimens were evaluated. Thus, the results of this portion of the program are contained in the measurements made on these 156 specimens, the description of these specimens, and the parameters which define the firing conditions in each test.

Table II contains a complete description of each specimen including composition, molding conditions, and post cure conditions. Reference is also supplied to the basic data sheet(s) which describe each specimen and its preparation.

Tables III-XV show the location of each specimen and the firing conditions of each test. The location chart identifies the motor and nozzle ends of the test section and the position of each test panel relative to the other specimens. In Figures 3-15 the motor pressure-time curves are reproduced for each firing test.

The measurements made on each specimen both before and after test and the average rates of surface erosion and char penetration are tabulated for each firing in Tables XVI through XXVIII. The visual appearance of each specimen is available for study in Figures 16 through 54. Each photograph shows the cross section of one set of four specimens and the mounting fixture which held these specimens after the unit was sectioned for examination. The original location of the surface of each specimen at the start of the motor test is shown by the dotted lines superimposed on the photograph by means of an overlay.

The complete output of the current portion of this program is contained in the figures and tabulations described. For those interested in the response of individual materials or their performance capability in an erosive environment typical of the nozzle entrance region these data should be carefully studied. In the following section a few of the more obvious comparisons and evaluations are offered as a general interpretation of the data. Other factors, such as detailed knowledge of the resin materials and behavior in other test environments, should be referred to, whenever available, by the serious reader.

5.0 DISCUSSION

A. REPRODUCIBILITY OF FIRING CONDITIONS

Each of the thirteen motor firings performed during the period covered by this report were made under the same nominal conditions. Some firing-to-firing variation was inevitable, of course, in terms of the exact firing conditions achieved. However, the uniformity of test conditions was found to be excellent. For the thirteen tests the average value of the motor pressure was 477 psia. All individual values fell within 6 percent of this pressure level. The average duration of a test was 31.0 seconds will all individual test durations being with 4 percent of this value. In light of the fact that these firings were made using low-cost procedures and gel propellant, the narrow range of conditions is exceptionally good. No significant variation in test results can be anticipated as a direct result of the observed variability in firing pressure or duration.

B. SELECTION OF STANDARD REINFORCEMENT ORIENTATION

In the first two firings covered in this report (ASD-9 and ASD-10) three replicate specimens of each of three different orientations of carbon cloth were tested. The objective was to select a preferred standard orientation of the reinforcement in the remaining specimens with which various candidate developmental resin binders would be compared. The three reinforcement orientations which were screened were paralled laminate, edge-oriented laminate, and chopped 3/8 inch cloth squares. The results obtained with these materials (see Tables 3 and 4) led to the following observations:

1. the edge-oriented specimens averaged about 1 mil/sec lower erosion rate than the parallel laminates,

2. the chopped cloth specimens (for the one-half inch thick specimens tested) eroded similarly to the edge-oriented specimens, and

3. both of the chopped squares and the parallel laminate orientation are subject to some swelling or delamination problem which requires some selective elimination of bad specimens which provide erratic data.

In addition to these comparisons on the basis of erosion behavior, it was found that quantitative char rate data could only be anticipated with the parallel laminate orientation of the carbon cloth reinforcement. With the other reinforcement orientations complete char-through occurred which leads only to the definition of a minimum char rate based on the total specimen thickness.

On the basis of these data, the parallel laminate orientation was selected for use in all the remaining specimens for this program. An important added consideration in this decision was the fact that fabrication of the flat laminate panels was much simpler and much less costly than the preparation of the edge-oriented specimens.

One other comparison provided by the results of firings ASD-9 and ASD-10 which was preliminary to the final selection of the standard reinforcement was the substitution of Pluton B and Pluton H for the carbon cloth in the parallel laminate construction. Based on the average of two specimens of each grade of Pluton (bonded with SC1008, a Mil R-9299 resin but not the standard used in other specimens) the Pluton B appeared inferior to carbon cloth while the Pluton H appeared slightly better. No justification could be seen, however, for using this more proprietary type of reinforcement as a standard of comparison rather than carbon cloth.

C. DELAMINATION IN FLAT LAMINATES

As indicated in the section above, the choice of the parallel laminate reinforcement was made for all specimens placed in the last eleven motor test firings (ASD-11 through ASD-21). The simplicity of this construction and the capability to measure char rates were sufficient reasons for this decision. Nonetheless, the price that had to be accepted was the ever-present danger of specimen delamination and blistering during test.

Several comments can be made about the delamination problem experienced in the various specimens. Of the 132 specimens contained in the last eleven firings, visible delaminations which had to be taken into account in the measurement of post test data were noted in 58. In about half of these instances no great uncertainty was introduced by these delaminations, but in the remaining specimens the performance measurement may well have been affected. In the final six firings an attempt was made to relieve any restraint along the edges of the specimens by placing a compliant filler in gaps left at the bevelled corners when the specimens were mounted. It was felt that edge-wise restraint of thermal growth might contribute to the buckling of the surface layers. However, no evidence was found that this possible restraint or the elimination of it played any role in the observed delaminations.

A positive relationship seemed to exist between the composition of the specimen and its tendency to delaminate during test. This can best be illustrated by a statistical summary of the extent to which various composites evidenced delamination. In the eleven tests under consideration a total of 33 sets of four replicate specimens were tested. One set was completely eroded away. Of the 32 sets which survived test, seven had no delaminations within the set, ten had either one or two specimens with delaminations, but fifteen sets had either three or all four specimens delaminated. Almost half of all the specimen sets, and sixty percent of those sets which exhibited some delamination, had either three or four specimens (out of four) delaminated. This summary is presented only because it suggests that the delamination tendency is related to the composition of the composite. It is reasonable to assume that laboratory fabrication procedures, which involve spatula coating of development resins onto carbon or graphite cloth, may yield less than optimum interlaminar bonding in the laminated specimens. The problem of laminar strength would be further aggravated by both the relatively refractory nature of some of the high temperature resins and the minimum of fabrication experience with them. Visual evidence, in the form of striations or incipient splits, were noted in many specimens prior to test. Two examples of partial delaminations pre-existent in specimens when received for test are shown in Figure 55. These pictures show the worst flaws noted in any

specimens, but a rather common occurrence was a noticeable striation at about one third of the thickness from each surface presumably related to a stacking procedure followed in the layup of the laminates.

The most logical conclusions that can be drawn from the evidence concerning delamination are two-fold:

1. Some delamination tendency is inherent in the test method when parallel cloth laminate specimens are tested, and

2. The interlaminar bond strength of individual specimens, as determined by the nature of the resin binder and the details of the fabrication procedure, affect the degree of delamination.

D. PERFORMANCE OF CONTROL STANDARD COMPOSITES

Two different standards were used as controls in the course of the eleven evaluation firings. Both control materials contained a commercial Mil R-9299 class phenolic resin; one composite was reinforced with carbon cloth and the other with graphite cloth. In each firing test a set of four replicate specimens of at least one of these controls was included, generally in the center test section. For the purposes of the discussion in this section and the next, the average char and erosion rates for each set of four replicate specimens are summarized for each of the firing tests in Table XXIX.

The phenolic-graphite cloth control was used in a total of six firings. In four of these (ASD-11, -13, -14, and -15) it was the only control; in two firings (ASD-12 and -21) the phenolic-carbon cloth composite was also included. The observed char and erosion rates in four of the tests were quite similar; the erosion rates averaged 4.5 mil/sec (maximum deviation 7%) and the char rates averaged 13.0 mil/sec (maximum deviation 6%). In the last two firing tests which contained phenolic-graphite control specimens higher rates of erosion (about 5.8 mil/sec) and charring (>14.8 mil/sec) were measured. It is possible that the higher rates of degradation were the result either of unusual severity in the test conditions or a variation in specimen quality; no convincing evidence is available to choose either explanation with certainty.

The phenolic-carbon control standard material was included in seven test firings (ASD-12 and ASD-16 through -21). In five tests it was the only control and in two both of the controls were present. In five of the seven tests the char and erosion rates were reproduced, the mean values being 11.6 mil/sec (maximum deviation 12%) and 4.6 mil/sec (maximum deviation 10%), respectively. In the remaining two tests the erosion rates were significantly different, one being unusually low (test ASD-17) and the other unusually high (test ASD-18). The char rates in these two tests were within the same range found in all tests. As was noted for the phenolic-graphite control, the divergent behavior of two of the phenolic-carbon control sets might have resulted from either undetected changes in test severity or from specimen variability. Some indirect evidence can be cited to support either assumption. First, delamination was as serious for the controls as for the experimental composites and the density of both of the controls (especially the phenolic-graphite) was rather low (see Table II) compared with the

normal value for commercial laminates which generally have a density of about 1.45 gm/cc. These factors might be taken to point to a variability in the specimen quality. On the other hand, in two tests in particular (ASD-15 and -18) the erosion rates of all the specimens were unusually high as well as the control specimens. Similarly, in ASD-17 the results all appear to trend downward in step with the phenolic-carbon control. Thus, it must be concluded that a moderate uncertainty, the source of which cannot be defined, remains in this motor test procedure as in virtually any exploratory series of tests. It is recommended to the reader that initial comparisons be made on the basis of the average data from each particular test. Whenever several tests are available, as is the case primarily for the control specimens in this program, the test to test variations can be dealt with effectively.

E. COMPARISON OF VARIOUS RESIN SYSTEMS

In this final section a summary of the comparisons which can be made concerning the performance potential of the various resin systems is given. The researcher directly involved in this area of study should feel free to study the data for additional insight into the behavior of the materials tested.

In order to provide a systematic discussion the resins examined are organized into four groups in terms of the basic nature of their chemical structure. The comments offered are based primarily on the comparison of the experimental materials with the control specimen data in the same firing as suggested above.

1. Phenolic Type Resins

A total of five developmental resins of the phenolic type were compared in tests with the standard (91 LD) phenolic. The relative performance of each of these when compared to the control standard is as follows:

Firing No.	Resin	Relation to Control Standard	
		Char Rate	Erosion Rate
13	Chrome phenolic	similar	similar
15	Tungsten-phenolic	similar	poorer
16	Naphthalene diol	poorer	better
19	Phenyl aldehyde	poorer	poorer
21	Biphenol formaldehyde	similar	poorer

The difficulty of improving upon the conventional phenolic with other phenolic modifications is apparent. Only the naphthalene diol resin provided a significant improvement in erosion resistance; some noticeable but probably not very important loss in charring resistance was noted.

In firing ASD-14 two grades of Pluton cloth were again compared, this time with the standard (91 LD) phenolic binder. The results contradict rather weakly the earlier comment (end of Section 5-B) in that the B grade looked a little more erosion resistant than the H grade. Overall, it is unlikely that any significant difference exists for the environment involved in this program.

2. Polyarylene Resins

Two resins appear to be best described as homopolymers of the polyarylene type. The performance comparison for these are:

Firing No.	Resin	Relation to Control Standard Char Rate	Erosion Rate
16	Polyphenyl	similar	similar
17	Polyphenylene	similar	poorer (similar to control average)

Here it must be concluded that no significant improvement was achieved over the existing standards.

3. Heterocyclic and Miscellaneous Aromatics

This category is meant to cover the two polyimide specimen sets (one with graphite cloth reinforcement and one with carbon cloth) and the two oxide-type polymers, diphenyl oxide and polyphenylene oxide. The latter set of specimens was completly eroded away during test and, thus, was the only material which must be judged as completely unacceptable in high erosion locations in a solid propellant motor. The comparisons of this group of resins with the standard may be outlined as follows:

Firing No.	Resin	Relation to Control Standard Char Rate	Erosion Rate
11	Polyimide (on graphite)	similar	poorer
17	Polyimide (on carbon)	poorer	similar (better than control average)
13	Diphenyl oxide	poorer	poorer
15	Polyphenylene oxide	very poor	very poor

This outline indicates that no advancement in the standard art was demonstrated in this series of resins.

4. Resin Blends

A total of seven specimen sets contained resin binders that can best be described as blends of two polymer structures. The performance measured for these is shown below. The first four materials were apparently formed by the simultaneous condensation of a mixed phenol material with formaldehyde. On the other hand, the last three materials were essentially mixtures of partially staged resins which are subjected to final cure together in the fabrication of the laminated test panels.

Firing No.	Resin	Relation to Control Standard Char Rate	Erosion Rate
11	Phenylphenol phenol formaldehyde	similar	better
12	2-7 dihydroxynaphthalene phenol formaldehyde	similar	similar
18	Polyphenylene phenolic	poorer	similar (poorer than control avg.)
18	Polyarylene phenolic	poorer	poorer

19	Epoxy/polyphenylene (intractable)	similar	poorer
20	Phenolic/polyphenylene (intractable)	poorer	better
20	P-phenylphenol phenol formaldehyde/polyphenylene (intractable)	similar	slightly better

In this group of resins more favorable results were noted than in the preceding groups. Several comments can be made. The phenylphenol phenol formaldehyde resin showed a significantly improved erosion resistance equalled only by the naphthalene diol resin in group 1, above. The 2-7 dihydroxynaphthalene phenol formaldehyde was only a stand-off with the commercial phenolic. The mixed polyarylene-phenolics (both the polyphenylene and the general polyarylene) were found inferior to the standard phenolic. The effect of the addition of the intractable polyphenylene in the last three specimen sets listed is rather difficult to interpret. In the epoxy system the performance was not up to the phenolic standard, but it is likely that the base epoxy would be even less suited for highly erosive service conditions. When mixed with the phenolic the intractable polyphenylene filler increased the char rate, but decreased the erosion rate. Lastly, the presence of the intractable polyphenylene in the p-phenylphenol phenol formaldehyde mixed resin provided performance slightly better than the standard phenolic but not as good as the system without the polyphenylene (the first material in this group) which is assumed to be similar.

TABLE I

CHARACTERISTICS OF ARCADENE 127A PROPELLANT[a]

Propellant Flame Temperature: 5700°F

Principal Combustion Products	Volume (percent)
CO_2	2.1
CO	22.2
H_2O	18.7
H_2	25.1
HCl	15.1
N_2	8.6
H	4.1
OH	1.5
AlCl	0.4
Cl	1.7
$Al_2O_3(l)$	27.4 gm/100 gm

[a]Theoretical data calculated for 500 psia chamber pressure.

TABLE II

DESCRIPTION OF TEST SPECIMENS

Specimen RTD No.	Hughes' Data Sheet No.	Resin	Reinforcement	Resin Content (weight %)	Molding Conditions: Pressure (psi)	Molding Conditions: Temperature (°F)	Molding Conditions: Time (min)	Postcure Cycle	Fabric Orientation	Specific Gravity
49-58	353	Phenolic (91 LD)	Carbon cloth CCA-1	42.4	200	300	240	a	Parallel	1.32
75, 76,	357	Phenolic	Carbon cloth	41.1	5,000	300	120	a	Edge	1.36
77, 78,	357	(91 LD)	CCA-1	41.5	5,000	300	120	a		1.37
79, 80	383			41.5	5,000	300	120	a		1.40
81, 82	-	Phenolic (SC 1008)	Pluton B	40.0	1,000	310	60	-	Parallel	-
83, 84	-	Phenolic (SC 1008)	Pluton H	40.0	1,000	310	60	-	Parallel	-
87, 88,	395b	Phenolic	Carbon cloth	40.8	10,000	200[1]-300	60[1]-60	a	Chopped squares	1.44
89, 90,	395b	(91 LD)	CCA-1	42.5	10,000	200[2]-300	45[2]-60	a		1.35
91, 92	395b			42.2	10,000	200[2]-300	45[2]-60	a		1.34
93, 94	367	Polyphenylene (Abchar 413)	Carbon cloth CCA-1	40.2	5,000	480	180	b	Edge	1.31
99-122	441/457	Phenolic (91 LD)	Graphite cloth G1550	36.4	180	300	180	a	Parallel	1.32
127, 128, 129, 130	437/451	Phenylphenol phenol formaldehyde resin	Graphite cloth G1550	36.2	300	300	120	a	Parallel	1.36
131, 132, 133, 134	434/442	Diphenyl oxide (QX-2682.1)	Graphite cloth G1550	37.0	200	350	120	c	Parallel	1.28
135, 136, 137, 138	435/445	Polyimide (Skygard 700)	Graphite cloth G1550	37.4	104	600	180	d	Parallel	1.17
139, 140, 141, 142	436/448	Chrome phenolic resin (Chrome P)	Graphite cloth G1550	36.2	104	180[3]-250	120[3]-300	e	Parallel	1.33
143, 144, 145, 146	438/454	2,7-Dihydroxy-naphthalene phenol formaldehyde resin	Graphite cloth G1550	38.0	300	300	120	f	Parallel	1.40
147, 148, 149, 150	-	Phenolic (91 LD)	Pluton B-1 fabric	39.0	1,000	300	180	a	Parallel	-
151, 152, 153, 154	-	Phenolic (91 LD)	Pluton H-1 fabric	41.3	1,000	300	180	a	Parallel	-
155, 156, 157, 158	488/497	Polyphenylene oxide resin	Graphite cloth G1550	35.4	500	600	180	None	Parallel	1.30
159, 160, 161, 162	487/494	Tungsten-phenolic (high tungsten)	Graphite cloth G1550	32.6	500	180[4]-250	45[4]-120	g	Parallel	1.46

TABLE II (continued)

Specimen RTD No.	Hughes' Data Sheet No.	Resin	Reinforcement	Resin Content (weight %)	Molding Conditions: Pressure (psi)	Molding Conditions: Temperature (°F)	Molding Conditions: Time (min)	Postcure Cycle	Fabric Orientation	Specific Gravity
163, 164, 165, 166	-	Polyphenyl (DP 25-10)	Carbon cloth CCA-1	26-27	1,000	325	120	h	Parallel	-
167, 168, 169, 170	-	Naphthalene diol (DP 32-13)	Carbon cloth CCA-1	35	300	275	120	i j	Parallel	-
171-194	500	Phenolic (91 LD)	Carbon cloth CCA-1	37.9	500	300	180	a	Parallel	1.38
199, 200, 201, 202	504	Polyphenylene (Abchar 413)	Carbon cloth CCA-1	36.6	300	400	120	k	Parallel	1.32
203, 204, 205, 206	501	Polyimide (F-170)	Carbon cloth CCA-1	33.6	300	600	120	l	Parallel	1.16
207, 208, 209, 210	502	Polyarylene phenolic (F-171)	Carbon cloth CCA-1	36.1	300	350	120	m	Parallel	1.32
211, 212, 213, 214	503	Polyphenylene phenolic (F-172)	Carbon cloth CCA-1	34.9	300	350	120	n	Parallel	1.32
215, 216, 217, 218	505	Phenyl aldehyde (DP-431	Carbon cloth CCA-1	37.3	500	300	120	a	Parallel	1.31
219, 220, 221, 222	506/515	Phenolic (91 LD) (intractable polyphenylene; Abchar 700 filler)[A]	Carbon cloth CCA-1	33.0	300	300	120	a	Parallel	1.32
223, 224, 225, 226	507/516	p-phenylphenol phenol formaldehyde resin (intractable polyphenylene; Abchar 700 filler)[A]	Carbon cloth CCA-1	30.9	300	300	120	a	Parallel	1.29
227, 228, 229, 230	508/517	Epoxy novalac resin (Den 438) (intractable polyphenylene; Abchar 700 filler)[A]	Carbon cloth CCA-1	[B]	300	300	120	o	Parallel	1.20
231, 232, 233, 234	-	Biphenol formaldehyde (EC-260)	Carbon cloth CCA-1	30.1	835	200-315[5]	30-30-160[5]	p	Parallel	1.47

TABLE II (concluded)

POSTCURE CYCLES

[a]18 hrs at 275°F, 72 hrs from 275°F to 400°F, 4 hrs at 400°F, 7 hrs cooling to below 200°F.

[b]18 hrs at 275°F, 108 hrs from 275°F to 600°F, cooled to below 200°F (postcured under helium atmosphere).

[c]16 hrs from room temperature to 275°F, 18 hrs at 275°F, 72 hrs from 275°F to 400°F, 9 hrs at 410°F to 490°F, 2 hrs at 500°F, 7 hrs cooling to below 200°F.

[d]24 hrs at 375°F, 24 hrs at 435°F, 24 hrs at 475°F, 24 hrs at 575°F, 6 hrs between temperatures, 7 hrs cooling to below 200°F.

[e]1 hr at 150°F, 1 hr at 200°F, 1 hr at 250°F, 1 hr at 300°F, 1 hr at 350°F, 2 hrs at 400°F, 7 hrs cooling to below 200°F.

[f]24 hrs at 275°F, 72 hrs from 275°F to 400°F, 4 hrs at 400°F, 7 hrs cooling to below 200°F.

[g]24 hrs from 100°F to 300°F, 1 hr at 300°F, 3 hrs from 300°F to 350°F, 1 hr at 350°F, 3 hrs from 350°F to 400°F, 2 hrs at 400°F, cool to below 200°F.

[h]24 hrs at 200°F, 24 hrs at 250°F, 24 hrs at 300°F, 24 hrs at 350°F.

[i]12 hrs at 200°F, 12 hrs at 250°F, 12 hrs at 300°F, 12 hrs at 350°F, 12 hrs at 400°F.

[j]12 hrs at 200°F, 12 hrs at 250°F, 12 hrs at 300°F, 12 hrs at 350°F.

[k]18 hrs at 275°F, 108 hrs from 275°F to 550°F, 6 hrs at 550°F, 7 hrs cooling to below 200°F. Parts were postcured in argon.

[l]24 hrs at each of the following temperatures: 375°F, 435°F, 475°F, and 575°F, 4 hrs at 700°F, 6 hrs between temperatures. Cool to below 200°F. Specimens postcured in argon.

[m]24 hrs at 375°F, 24 hrs at 435°F, 24 hrs at 475°F, 24 hrs at 575°F, 4 hrs at 700°F (6 hrs between temperatures), 10 hrs cooling to below 200°F. Specimens postcured in argon.

[n]16 hrs at 275°F, 72 hrs from 275°F to 400°F, 6 hrs from 400°F to 450°F, 4 hrs at 450°F, 6 hrs from 450°F to 500°F, 12 hrs at 500°F, cool to below 200°F.

[o]18 hrs at 275°F, 6 hrs from 275°F to 400°F, 1 hr at 400°F, 7 hrs cooling to below 200°F.

[p]72 hrs at 200°F, 72 hrs at 225°F, 72 hrs at 250°F, 72 hrs at 275°F, and 48 hrs at 300°F.

MOLDING CONDITIONS

[1]Cured for 1 hr at 200°F and 1 hr at 300°F.

[2]Cured for 45 min at 200°F and 1 hr at 300°F.

[3]Cured for 2 hrs at 180°F and 5 hrs at 250°F.

[4]Cured for 45 min at 180°F and 2 hrs at 250°F.

[5]Cured for 30 min at 200°F, then 30 min to 315°F and held there for 4 hrs.

RESIN COMPOSITION

[A]Resin - filler ratio, 2:1 by weight.

[B]Final resin content not possible to determine because of weight loss due to reaction between epoxy resin catalyst and Abchar 700.

TABLE III

LOCATION OF SPECIMENS TESTED
IN FIRING ASD-9

Maximum Pressure - 554 psia

Average Pressure - 477 psia

Time - 31.9 seconds

ROCKET NOZZLE

RTD #82 Phenolic/Pluton B Parallel	RTD #78 Phenolic/Carbon Edge Grain	RTD #52 Phenolic/Carbon Parallel	RTD #90 Phenolic/Carbon Chopped Squares
RTD #84 Phenolic/Pluton H Parallel	RTD #79 Phenolic/Carbon Edge Grain	RTD #53 Phenolic/Carbon Parallel	RTD #91 Phenolic/Carbon Chopped Squares
RTD #94 Polyphenylene/ Carbon Edge Grain	RTD #80 Phenolic/Carbon Edge Grain	RTD #54 Phenolic/Carbon Parallel	RTD #92 Phenolic/Carbon Chopped Squares

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TABLE IV

LOCATION OF SPECIMENS TESTED
IN FIRING ASD-10

Maximum Pressure - 523 psia

Average Pressure - 460 psia

Time - 32.1 seconds

ROCKET NOZZLE

RTD #81 Phenolic/Pluton B Parallel	RTD #75 Phenolic/Carbon Edge Grain	RTD #49 Phenolic/Carbon Parallel	RTD #87 Phenolic/Carbon Chopped Squares
RTD #83 Phenolic/Pluton H Parallel	RTD #76 Phenolic/Carbon Edge Grain	RTD #50 Phenolic/Carbon Parallel	RTD #88 Phenolic/Carbon Chopped Squares
RTD #93 Polyphenylene/ Carbon Edge Grain	RTD #77 Phenolic/Carbon Edge Grain	RTD #51 Phenolic/Carbon Parallel	RTD #89 Phenolic/Carbon Chopped Squares

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TABLE V

LOCATION OF SPECIMENS[a] TESTED IN FIRING ASD-11

Maximum Pressure - 527 psia

Average Pressure - 490 psia

Time - 30.1 seconds

ROCKET NOZZLE

RTD #127 Phenylphenol phenol formaldehyde/graphite cloth	RTD #128 → same	RTD #129 → same	RTD #130 → same
RTD #102 Phenolic/graphite cloth → same	RTD #104 → same	RTD #105 → same	RTD #106 → same
RTD #135 Polyimide/graphite cloth → same	RTD #136 → same	RTD #137 → same	RTD #138 → same

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[a] All specimens were flat laminate construction.

TABLE VI

LOCATION OF SPECIMENS[a] TESTED IN FIRING ASD-12

Maximum Pressure - 520 psia

Average Pressure - 475 psia

Time - 31.1 seconds

ROCKET NOZZLE

RTD #143 2,7-Dihydroxy-naphthalene phenolic/graphite cloth	RTD #144 → same	RTD #145 → same	RTD #146 → same
RTD #99 Phenolic/graphite cloth	RTD #100 → same	RTD #101 → same	RTD #102 → same
RTD #55 Phenolic/carbon cloth	RTD #56 → same	RTD #57 → same	RTD #58 → same

MOTOR CHAMBER

[a]All specimens were flat laminate construction.

TABLE VII

LOCATION OF SPECIMENS[a] TESTED IN FIRING ASD-13

Maximum Pressure - 515 psia

Average Pressure - 460 psia

Time - 30.2 seconds

ROCKET NOZZLE

RTD #131 Diphenyl oxide/ graphite cloth	RTD #132 → same	RTD #133 → same	RTD #134 → same
RTD #107 Phenolic/graphite cloth	RTD #108 → same	RTD #109 → same	RTD #110 → same
RTD #139 Chrome phenolic/ graphite cloth	RTD #140 → same	RTD #141 → same	RTD #142 → same

MOTOR CHAMBER

[a]All specimens were flat laminate construction.

TABLE VIII

LOCATION OF SPECIMENS[a] TESTED IN FIRING ASD-14

Maximum Pressure - 542 psia

Average Pressure - 483 psia

Time - 31.3 seconds

ROCKET NOZZLE

RTD #147 Phenolic/Pluton B-1 cloth	RTD #148 → same	RTD #149 → same	RTD #150 → same
RTD #111 Phenolic/graphite cloth	RTD #112 → same	RTD #113 → same	RTD #114 → same
RTD #151 Phenolic/Pluton H-1 cloth	RTD #152 → same	RTD #153 → same	RTD #154 → same

MOTOR CHAMBER

[a] All specimens were flat laminate construction.

TABLE IX

LOCATION OF SPECIMENS[a] TESTED IN FIRING ASD-15

Maximum Pressure - 545 psia

Average Pressure - 480 psia

Time - 31.0 seconds

ROCKET NOZZLE

RTD #155 Polyphenylene oxide/graphite cloth	RTD #156 → same	RTD #157 → same	RTD #158 → same
RTD #115 Phenolic/ graphite cloth	RTD #116 → same	RTD #117 → same	RTD #118 → same
RTD #159 Tungsten-phenolic resin/graphite cloth	RTD #160 → same	RTD #161 → same	RTD #162 → same

MOTOR CHAMBER

[a]All specimens were flat laminate construction.

TABLE X

LOCATION OF SPECIMENS[a] TESTED IN FIRING ASD-16

Maximum Pressure - 523 psia

Average Pressure - 460 psia

Time - 32.0 seconds

ROCKET NOZZLE

RTD #163 Polyphenyl/ carbon cloth →	RTD #164 → same	RTD #165 → same	RTD #166 → same
RTD #171 Phenolic/carbon cloth →	RTD #172 → same	RTD #173 → same	RTD #174 → same
RTD #167 Naphthalene diol/ carbon cloth →	RTD #168 → same	RTD #169 → same	RTD #170 → same

MOTOR CHAMBER

[a]All specimens were flat laminate construction.

TABLE XI

LOCATION OF SPECIMENS[a] TESTED IN FIRING ASD-17

Maximum Pressure - 492 psia

Average Pressure - 455 psia

Time - 31.8 seconds

ROCKET NOZZLE

RTD #199 Polyphenylene/ carbon cloth	RTD #200 → same	RTD #201 → same	RTD #202 → same
RTD #175 Phenolic/carbon cloth	RTD #176 → same	RTD #177 → same	RTD #178 → same
RTD #203 Polyimide/carbon cloth	RTD #204 → same	RTD #205 → same	RTD #206 → same

MOTOR CHAMBER

[a] All specimens were flat laminate construction.

TABLE XII

LOCATION OF SPECIMENS[a] TESTED IN FIRING ASD-18

Maximum Pressure - 527 psia

Average Pressure - 478 psia

Time - 30.5 seconds

ROCKET NOZZLE

RTD #211 Polyphenylene phenolic/carbon cloth	RTD #212 → same	RTD #213 → same	RTD #214 → same
RTD #179 Phenolic/carbon cloth	RTD #180 → same	RTD #181 → same	RTD #182 → same
RTD #207 Polyarylene phenolic/carbon cloth	RTD #208 → same	RTD #209 → same	RTD #210 → same

MOTOR CHAMBER

[a]All specimens were flat laminate construction.

TABLE XIII

LOCATION OF SPECIMENS[a] TESTED IN FIRING ASD-19

Maximum Pressure - 535 psia

Average Pressure - 505 psia

Time - 30.4 seconds

ROCKET NOZZLE

RTD #215 Phenyl Aldehyde/ carbon cloth	RTD #216 → same	RTD #217 → same	RTD #218 → same
RTD #183 Phenolic/carbon cloth	RTD #184 → same	RTD #185 → same	RTD #186 → same
RTD #227 Epoxy/poly-phenylene/ (intractable) carbon cloth	RTD #228 → same	RTD #229 → same	RTD #230 → same

MOTOR CHAMBER

[a]All specimens were flat laminate construction.

TABLE XIV

LOCATION OF SPECIMENS[a] TESTED IN FIRING ASD-20

Maximum Pressure - 527 psia

Average Pressure - 480 psia

Time - 30.4 seconds

ROCKET NOZZLE

RTD #219 Phenolic/poly-phenylene/ (intractable) carbon cloth	RTD #220 → same	RTD #221 → same	RTD #222 → same
RTD #187 Phenolic/ carbon cloth	RTD #188 → same	RTD #189 → same	RTD #190 → same
RTD #223 p-phenylphenol phenol formalde-hyde/polyphenylene/ (intractable) carbon cloth	RTD #224 → same	RTD #225 → same	RTD #226 → same

MOTOR CHAMBER

[a]All specimens were flat laminate construction.

TABLE XV

LOCATION OF SPECIMENS[a] TESTED IN FIRING ASD-21

Maximum Pressure - 542 psia

Average Pressure - 501 psia

Time - 30.8 seconds

ROCKET NOZZLE

RTD #119 Phenolic/graphite cloth	RTD #120 → same	RTD #121 → same	RTD #122 → same
RTD #231 Biphenol formaldehyde/ carbon cloth	RTD #232 → same	RTD #233 → same	RTD #234 → same
RTD #191 Phenolic/ carbon cloth	RTD #192 → same	RTD #193 → same	RTD #194 → same

MOTOR CHAMBER

[a]All specimens were flat laminate construction.

TABLE XVI

QUANTITATIVE DATA FROM FIRING ASD-9

Specimen No.	Specimen Composition	Thickness (inch)				Char Rate (mil/sec)	Erosion Rate (mil/sec)
		Initial	Final	Char	Uncharred		
82	Phenolic/Pluton B Cloth (parallel)	.498	.262[a]	.061	.201	9.3	7.4
78	Phenolic/Carbon Cloth (edge)	.503	.344	.344	.000	>15.8	5.0
52	Phenolic/Carbon Cloth (parallel)	.500	.358[b]	.151	.207	9.2	4.4
90	Phenolic/Carbon Cloth (chopped squares)	.504	.389	.389	.000	>15.8	3.6
84	Phenolic/Pluton H Cloth (parallel)	.498	.329	.187	.142	11.2	5.3
79	Phenolic/Carbon Cloth (edge)	.504	.400	.400	.000	>15.8	3.3
53	Phenolic/Carbon Cloth (parallel)	.502	.316	.206	.110	12.3	5.8
91	Phenolic/Carbon Cloth (chopped squares)	.505	.384	.384	.000	>15.8	3.7

TABLE XVI (continued)

Specimen No.	Specimen Composition	Thickness (inch)				Char Rate (mil/sec)	Erosion Rate (mil/sec)
		Initial	Final	Char	Uncharred		
94	Polyphenylene/Carbon Cloth (edge)	.503	.333	.333	.000	>15.8	5.3
80	Phenolic/Carbon Cloth (edge)	.503	.369	.369	.000	>15.8	4.2
54	Phenolic/Carbon Cloth (parallel)	.502	.331[b]	.201	.130	11.7	5.4
92	Phenolic/Carbon Cloth (chopped squares)	.502	.379	.379	.000	>15.7	3.9

[a]Delaminated thickness neglected and not included as part of final thickness.

[b]Measurement of remaining materials by parts (i.e., by sum of thickness of solid material) to eliminate effects of voids.

TABLE XVII

QUANTITATIVE DATA FROM FIRING ASD-10

Specimen	Specimen Composition	Thickness (inch)				Char Rate (mil/sec)	Erosion Rate (mil/sec)
		Initial	Final	Char	Uncharred		
81	Phenolic/Pluton B Cloth (parallel)	.470	.331	.186	.145	10.0	4.3
75	Phenolic/Carbon Cloth (edge)	.503	.385	.385	.000	>15.7	3.7
49	Phenolic/Carbon Cloth (parallel)	.502	.327[a]	.122	.205	9.3	5.5
87	Phenolic/Carbon Cloth (chopped squares)	.502	.316	.316	.000	>15.6	5.8
83	Phenolic/Pluton H Cloth (parallel)	.525	.396[b]	.157	.239	8.9	4.0
76	Phenolic/Carbon Cloth (edge)	.503	.376	.376	.000	>15.7	4.0
50	Phenolic/Carbon Cloth (parallel)	.503	.358[a]	.085	.273	7.2	4.5
88	Phenolic/Carbon Cloth (chopped squares)	.503	.399	.399	.000	>15.7	3.2
93	Polyphenylene/Carbon Cloth (edge)	.502	.363	.363	.000	>15.6	4.3
77	Phenolic/Carbon Cloth (edge)	.502	.374	.374	.000	>15.6	4.0
51	Phenolic/Carbon Cloth (parallel)	.500	.344[a]	.076	.268	7.2	4.9
89	Phenolic/Carbon Cloth (chopped squares)	.502	.418	.418	.000	>15.6	2.9

[a]Delaminated thickness neglected and not included as part of final thickness.

[b]Measurement of remaining materials by parts (i.e., by sum of thickness of solid material) to eliminate effects of voids

TABLE XVIII

QUANTITATIVE DATA FROM FIRING ASD-11

Specimen No.	Thickness (inch)				Char Rate (mil/sec)	Erosion Rate (mil/sec)
	Initial	Final	Char	Uncharred		
Phenylphenol phenol formaldehyde/graphite cloth (parallel)						
127	.504	.401	.275	.126	12.6	3.4
128	.503	.395	.319	.076	14.2	3.6
129	.503	.408	.296	.112	13.0	3.2
130	.503	.410	.318	.092	13.7	3.1
Phenolic/graphite cloth (parallel)						
103	.503	.398	.340	.058	14.8	3.5
104	.503	.387	.305	.082	14.0	3.9
105	.502	.352[a]	.234	.118	13.0	5.0
106	.503	.373[a]	.263	.110	13.1	4.3
Polyimide/graphite cloth (parallel)						
135	.503	.346	.261	.085	13.9	5.2
136	.500	.340	.244	.096	13.4	5.3
137	.502	.342	.253	.089	13.7	5.3
138	.501	.359	.250	.109	13.0	4.7

[a]Measurement of remaining materials by parts (i.e., by sum of thickness of solid material) to eliminate effect of voids.

TABLE XIX

QUANTITATIVE DATA FROM FIRING ASD-12

Specimen No.	Thickness (inch)				Char Rate (mil/sec)	Erosion Rate (mil/sec)
	Initial	Final	Char	Uncharred		
2,7-Dihydroxynaphthalene phenolic/graphite cloth (parallel)						
143	.503	.368[a]	.244	.124	12.2	4.3
144	.504	.369[b]	.256	.113	12.6	4.3
145	.503	.375[a]	.274	.101	12.9	4.1
146	.503	.353[a]	.207	.146	11.5	4.8
Phenolic/graphite cloth (parallel)						
99	.504	.353[a]	.251	.104	12.9	4.9
100	.501	.386[b]	.255	.131	11.9	3.7
101	.502	.350	.350	.000	>16.1	4.9
102	.503	.367[a]	.199	.168	10.8	4.4
Phenolic/carbon cloth (parallel)						
55	.503	.380	.206	.174	10.6	4.0
56	.503	.380	.184	.196	9.9	4.0
57	.504	.367	.213	.154	11.2	4.4
58	.502	.417	.219	.198	9.8	2.7

[a]Measurement of remaining materials by parts (i.e., by sum of thickness of solid material) to eliminate effect of voids.

[b]Delaminated thickness neglected and not included as part of final thickness.

TABLE XX

QUANTITATIVE DATA FROM FIRING ASD-13

Specimen No.	Thickness (inch) Initial	Final	Char	Uncharred	Char Rate (mil/sec)	Erosion Rate (mil/sec)
Diphenyl oxide/graphite cloth (parallel)						
131	.502	.346[b]	.270	.076	14.1	5.1
132	.502	.347[a]	.260	.087	13.7	5.1
133	.502	.397	.397	.000	>16.6	3.5
134	.500	.341[a]	.341	.000	>16.6	5.3
Phenolic/graphite cloth (parallel)						
107	.503	.347[a]	.235	.112	13.0	5.2
108	.502	.369[b]	.255	.114	12.8	4.4
109	.503	.427	.290	.137	12.1	2.5
110	.503	.379[b]	.241	.138	12.1	4.1
Chrome phenolic/graphite cloth (parallel)						
139	.503	.337[a]	.283	.054	14.9	5.5
140	.503	.366	.280	.086	13.8	4.5
141	.503	.365	.305	.060	14.7	4.6
142	.502	.382[b]	.197	.185	10.5	4.0

[a] Measurement of remaining materials by parts (i.e., by sum of thickness of solid material) to eliminate effect of voids.

[b] Delaminated thickness neglected and not included as part of final thickness.

TABLE XXI

QUANTITATIVE DATA FROM FIRING ASD-14

Specimen No.	Thickness (inch)				Char Rate (mil/sec)	Erosion Rate (mil/sec)
	Initial	Final	Char	Uncharred		
Phenolic/Pluton B-1 cloth (parallel)						
147	.500	.375	.249	.126	11.9	4.0
148	.499	.367	.250	.117	12.2	4.2
149	.502	.389	.253	.136	11.7	3.6
150	.503	.337	.231	.106	12.7	5.3
Phenolic/graphite cloth (parallel)						
111	.501	.331[a b]	.242	.089	13.2	5.4
112	.502	.360	.258	.102	12.8	4.5
113	.503	.282[b]	.282	.000	>16.1	7.1
114	.502	.362[a]	.241	.121	12.2	4.5
Phenolic/Pluton H-1 cloth (parallel)						
151	.492	.338	.250	.088	12.9	4.9
152	.492	.357	.249	.108	12.3	4.3
153	.498	.335[a]	.187	.148	11.2	5.2
154	.498	.360[a]	.215	.145	11.3	4.4

[a] Measurement of remaining materials by parts (i.e., by sum of thickness of solid material) to eliminate effect of voids.

[b] Delaminated thickness neglected and not included as part of final thickness.

TABLE XXII

QUANTITATIVE DATA FROM FIRING ASD-15

Specimen No.	Thickness (inch) Initial	Final	Char	Uncharred	Char Rate (mil/sec)	Erosion Rate (mil/sec)
Polyphenylene oxide/graphite cloth (parallel)						
155	Completely eroded					
156	Completely eroded					
157	Completely eroded					
158	Completely eroded					
Phenolic/graphite cloth (parallel)						
115	.505	.345	.275	.070	14.0	5.2
116	.505	.354	.246	.108	12.8	4.9
117	.505	.288	.288	.000	>16.3	7.0
118	.505	.300	.300	.000	>16.3	6.6
Tungsten-phenolic/graphite cloth (parallel)						
159	.504	.312	.210	.102	13.0	6.2
160	.504	.302	.206	.096	13.2	6.5
161	.504	.263[a]	.179	.084	13.5	7.8
162	.504	.264	.130	.134	11.9	7.7

[a]Measurement of remaining material by parts (i.e., by sum of thickness of solid material) to eliminate effect of voids.

TABLE XXIII

QUANTITATIVE DATA FROM FIRING ASD-16

Specimen No.	Thickness (inch)				Char Rate (mil/sec)	Erosion Rate (mil/sec)
	Initial	Final	Char	Uncharred		
Polyphenyl/carbon cloth (parallel)						
163	.506	.360[a]	.164	.196	9.7	4.6
164	.511	.318[a]	.196	.122	12.2	6.0
165	.509	.387	.253	.134	11.7	3.8
166	.514	.362[a]	.195	.167	10.8	4.7
Phenolic/carbon cloth (parallel)						
171	.502	.354	.249	.105	12.4	4.6
172	.502	.423[a]	.278	.145	11.2	2.5
173	.502	.361	.270	.091	12.8	4.4
174	.502	.368[a]	.166	.202	9.4	4.2
Naphthalene diol/carbon cloth (parallel)						
167	.475	.413[a]	.267	.146	10.3	1.9
168	.472	.381	.381	.000	>14.8	2.8
169	.475	.383	.383	.000	>14.8	2.9
170	.477	.384[a]	.260	.124	11.0	2.9

[a]Measurement of remaining material by part (i.e., by sum of thickness of solid material) to eliminate effect of voids.

TABLE XXIV

QUANTITATIVE DATA FROM FIRING ASD-17

Specimen No.	Thickness (inch)				Char Rate (mil/sec)	Erosion Rate (mil/sec)
	Initial	Final	Char	Uncharred		
Polyphenylene/carbon cloth (parallel)						
199	.504	.381	.239	.142	11.4	3.9
200	.503	.339	.194	.145	11.2	5.2
201	.504	.388[a]	.229	.159	10.8	3.6
202	.503	.342	.202	.140	11.4	5.1
Phenolic/carbon cloth (parallel)						
175	.501	.391	.246	.145	11.2	3.5
176	.501	.387[a]	.199	.188	9.8	3.6
177	.502	.409	.251	.158	10.8	2.9
178	.500	.396	.244	.152	10.9	3.3
Polyimide/carbon cloth (parallel)						
203	.504	.412	.344	.068	13.7	2.9
204	.502	.406	.345	.061	13.9	3.0
205	.502	.382	.309	.073	13.5	3.8
206	.504	.398	.322	.076	13.5	3.3

[a]Measurement of remaining materials by parts (i.e., by sum of thickness of solid material) to eliminate effect of voids.

TABLE XXV

QUANTITATIVE DATA FROM FIRING ASD-18

Specimen No.	Thickness (inch)				Char Rate (mil/sec)	Erosion Rate (mil/sec)
	Initial	Final	Char	Uncharred		
Polyphenylene phenolic/carbon cloth (parallel)						
211	.502	.296[a]	.222	.074	14.0	6.8
212	.503	.295[a]	.239	.056	14.7	6.8
213	.503	.280[a]	.201	.081	13.9	7.3
214	.503	.310[a]	.260	.050	14.8	6.3
Phenolic/carbon cloth (parallel)						
179	.502	.323[a]	.156	.167	11.0	5.9
180	.502	.261[a]	.109	.152	11.5	7.9
181	.503	.311[a]	.149	.162	11.2	6.3
182	.503	.274[a]	.222	.052	14.8	7.5
Polyarylene phenolic/carbon cloth (parallel)						
207	.503	.241[a]	.146	.095	13.4	8.6
208	.502	.253	.186	.067	14.3	8.2
209	.504	.318[a]	.211	.107	13.0	6.1
210	.502	.279[a]	.208	.071	14.1	7.3

[a]Measurement of remaining materials by parts (i.e., by sum of thicknesses of solid material) to eliminate effect of voids.

TABLE XXVI

QUANTITATIVE DATA FROM FIRING ASD-19

Specimen No.	Thickness (inch) Initial	Final	Char	Uncharred	Char Rate (mil/sec)	Erosion Rate (mil/sec)
Phenyl aldehyde/carbon cloth (parallel)						
215	.504	.337[a]	.288	.049	15.0	5.5
216	.505	.239[a]	.176	.063	13.9	8.7
217	.505	.201[a]	.201	.000	>16.6	10.0
218	.504	.302[a]	.302	.000	>16.6	6.6
Phenolic/carbon cloth (parallel)						
183	.503	.371	.271	.100	13.3	4.3
184	.502	.173[a]	.090	.083	13.8	10.8
185	.502	.367	.291	.076	14.0	4.4
186	.502	.303	.178	.142	11.8	6.5
Epoxy/polyphenylene (intractable)/carbon cloth (parallel)						
227	.503	.168[a]	.100	.068	14.3	11.0
228	.504	.244[a]	.167	.077	14.0	8.6
229	.503	.280[a]	.162	.118	12.7	7.3
230	.502	.299[a]	.162	.137	12.0	6.7

[a]Measurement of remaining material by parts (i.e., by sum of thickness of solid material) to eliminate effect of voids.

TABLE XXVII

QUANTITATIVE DATA FROM FIRING ASD-20

Specimen No.	Thickness (inch)				Char Rate (mil/sec)	Erosion Rate (mil/sec)
	Initial	Final	Char	Uncharred		
Phenolic/polyphenylene (intractable)/carbon cloth (parallel)						
219	.503	.363	.269	.094	13.5	4.6
220	.504	.410	.294	.116	12.8	3.1
221	.505	.350	.238	.112	12.9	5.1
222	.504	.398	.277	.121	12.6	3.5
Phenolic/carbon cloth (parallel)						
187	.503	.408[a]	.280	.128	12.3	3.1
188	.505	.329[a]	.129	.200	10.0	5.8
189	.504	.323[a]	.189	.134	12.2	6.0
190	.503	.388[a]	.225	.163	11.2	3.8
p-phenylphenol phenol formaldehyde/polyphenylene (intractable)/carbon cloth (parallel)						
223	.504	.346[a]	.214	.132	12.2	5.2
224	.505	.394[a]	.240	.154	11.5	3.7
225	.504	.382	.240	.142	11.9	4.0
226	.504	.376	.225	.151	11.6	4.2

[a]Measurement of remaining material by parts (i.e., by sum of thickness of solid material) to eliminate effect of voids.

TABLE XXVIII

QUANTITATIVE DATA FROM FIRING ASD-21

Specimen No.	Thickness (inch)				Char Rate (mil/sec)	Erosion Rate (mil/sec)
	Initial	Final	Char	Uncharred		
Phenolic/graphite cloth (parallel)						
119	.502	.333[a]	.238	.095	13.2	5.5
120	.503	.329[a]	.329	.000	>16.3	5.7
121	.506	.282[a]	.282	.000	>16.4	7.3
122	.504	.371[a]	.291	.080	13.8	4.3
Biphenol formaldehyde/carbon cloth (parallel)						
231	.544	.279[a]	.140	.139	13.2	8.6
232	.543	.271[a]	.128	.143	13.0	8.8
233	.544	.299[a]	.165	.134	13.3	8.0
234	.541	.266	.156	.110	14.0	8.9
Phenolic/carbon cloth (parallel)						
191	.503	.407	.261	.146	11.6	3.1
192	.501	.398[a]	.237	.161	11.0	3.3
193	.502	.294[a]	.171	.123	12.3	6.8
194	.499	.333[a]	.236	.097	13.1	5.4

[a]Measurement of remaining material by parts (i.e., by sum of thickness of solid material) to eliminate effect of voids.

TABLE XXIX

SUMMARY COMPARISON OF MATERIALS PERFORMANCE

Material	Avg. Char Rate (mil/sec)	Avg. Erosion Rate (mil/sec)
Phenolic/graphite control (overall average from four tests)	13.0	4.5
Phenolic/carbon control (overall average from five tests)	11.6	4.6
Firing ASD-11		
Phenylphenol phenol formaldehyde/ graphite cloth	13.4	3.3
Phenolic/graphite cloth	13.7	4.2
Polyimide/graphite cloth	13.5	5.1
Firing ASD-12		
2,7-dihydroxynapthalene phenol formaldehyde/graphite cloth	12.3	4.4
Phenolic/graphite cloth	12.9	4.5
Phenolic/carbon cloth	10.6[a]	4.1[a]
Firing ASD-13		
Diphenyl oxide/graphite cloth	14.8[a]	5.2[a]
Phenolic/graphite cloth	12.6[a]	4.6[a]
Chrome phenolic/graphite cloth	13.5	4.6
Firing ASD-14		
Phenolic/pluton B-1 cloth	12.1	4.3
Phenolic/graphite cloth	12.7[a]	4.8[a]
Phenolic/pluton H-1 cloth	11.9	4.7

[a]Calculated after eliminating single divergent result, based on erosion rate.

TABLE XXIX (continued)

Material	Avg. Char Rate (mil/sec)	Avg. Erosion Rate (mil/sec)
Firing ASD-15		
Polyphenylene oxide/ graphite cloth	(completely eroded away)	>15.
Phenolic/graphite cloth	>14.8	5.9
Tungsten-P resin/graphite cloth	12.9	7.0
Firing ASD-16		
Polyphenyl/carbon cloth	11.1	4.8
Phenolic/carbon cloth	11.2[a]	4.4[a]
Napthalene diol/carbon cloth	>13.5[a]	2.9[a]
Firing ASD-17		
Polyphenylene/carbon cloth	11.2	4.5
Phenolic/carbon cloth	10.7	3.3
Polyimide/carbon cloth	13.7	3.3
Firing ASD-18		
Polyphenylene phenolic/carbon cloth	14.4	6.8
Phenolic/carbon cloth	12.1	6.9
Polyarylene phenolic/carbon cloth	13.7	7.6
Firing ASD-19		
Phenyl aldehyde/carbon cloth	>15.5	7.7
Phenolic/carbon cloth	13.0[a]	5.1[a]
DEN 438/Abchar 700/carbon cloth	12.9[a]	7.5[a]

[a]Calculated after eliminating single divergent result, based on erosion rate.

TABLE XXIX (concluded)

Material	Avg. Char Rate (mil/sec)	Avg. Erosion Rate (mil/sec)
Firing ASD-20		
Phenolic/Abchar 700/carbon cloth	13.0	4.1
Phenolic/carbon cloth	11.4	4.7
p-phenylphenol phenol formaldehyde/ Abchar 700/carbon cloth	11.8	4.3
Firing ASD-21		
Phenolic/graphite cloth	>14.9	5.7
Biphenol formaldehyde/carbon cloth	13.4	8.6
Phenolic/carbon cloth	12.0	4.7

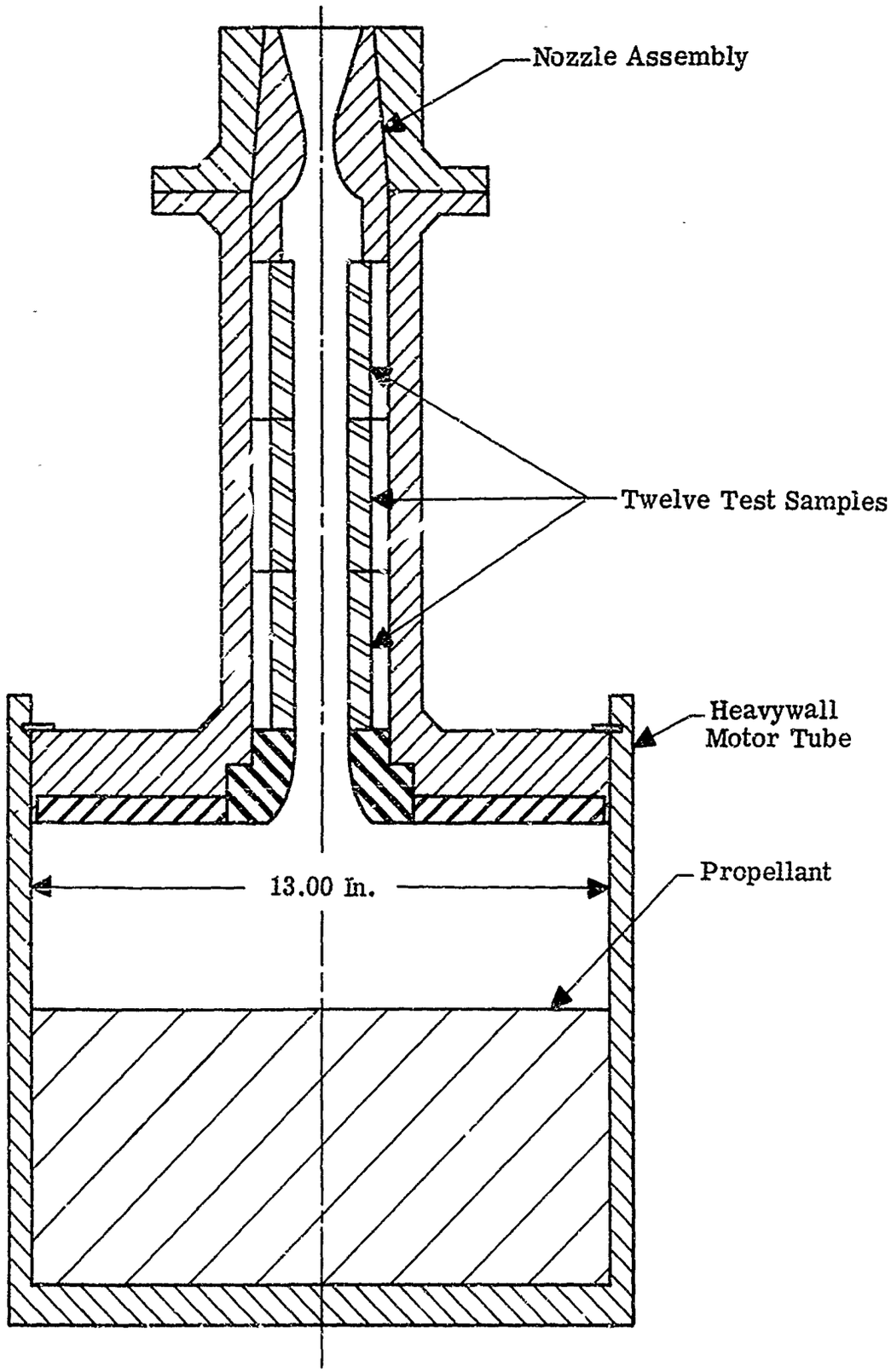


Figure 1. High Velocity Materials Evaluation Motor Assembly.

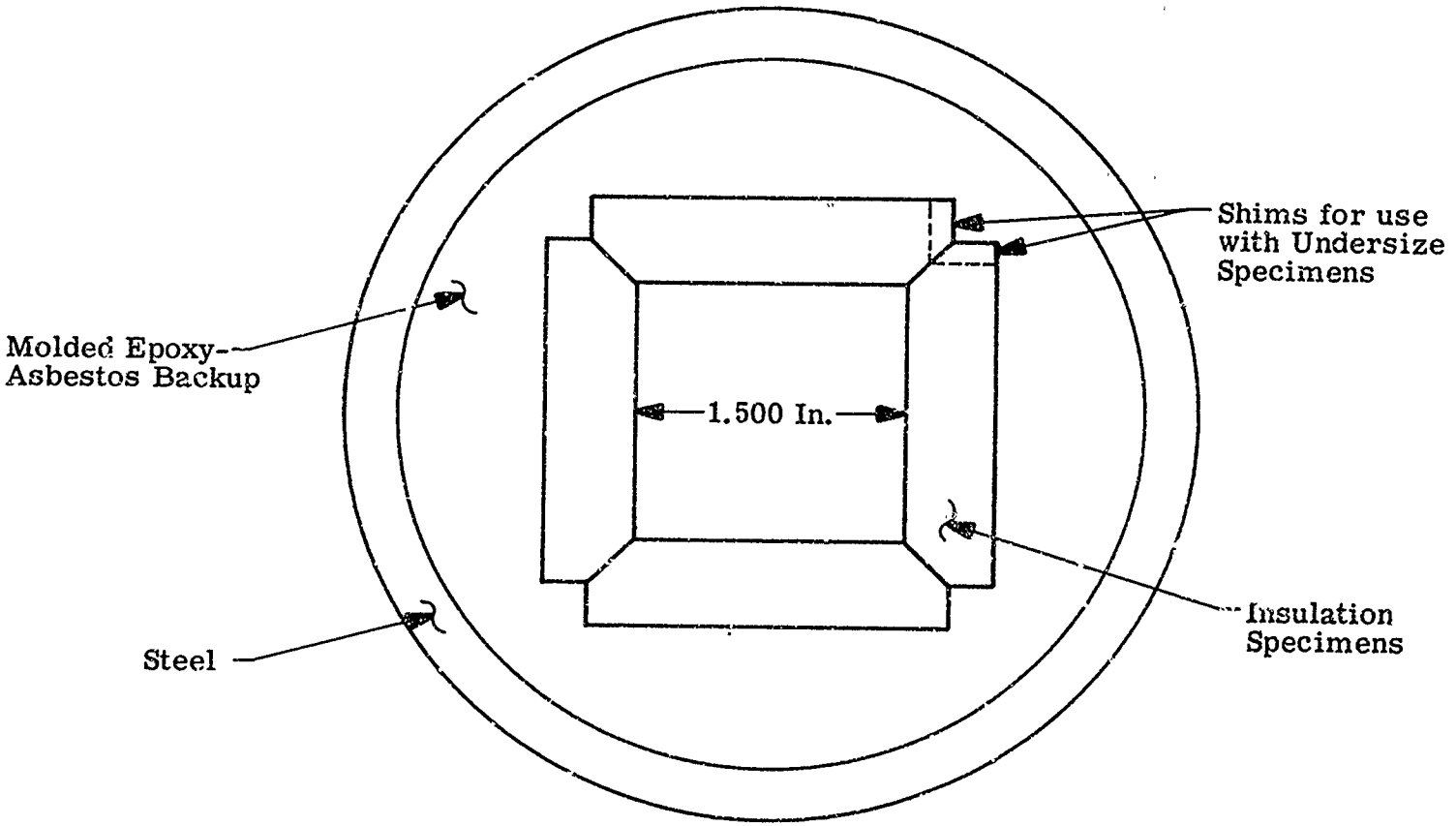


Figure 2. Specimen Mounting Configuration.

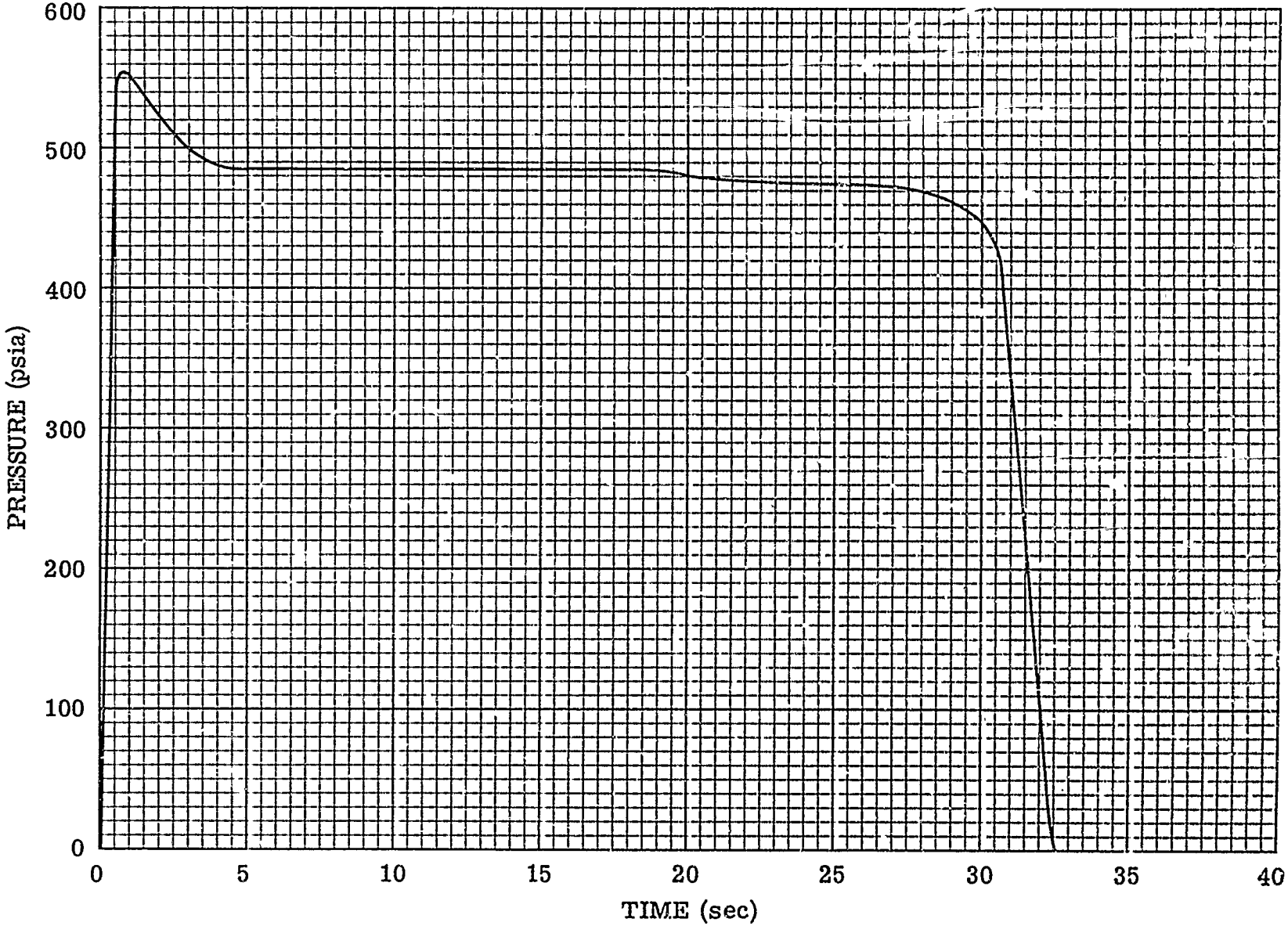


Figure 3. Motor Pressure Trace for Firing ASD-9

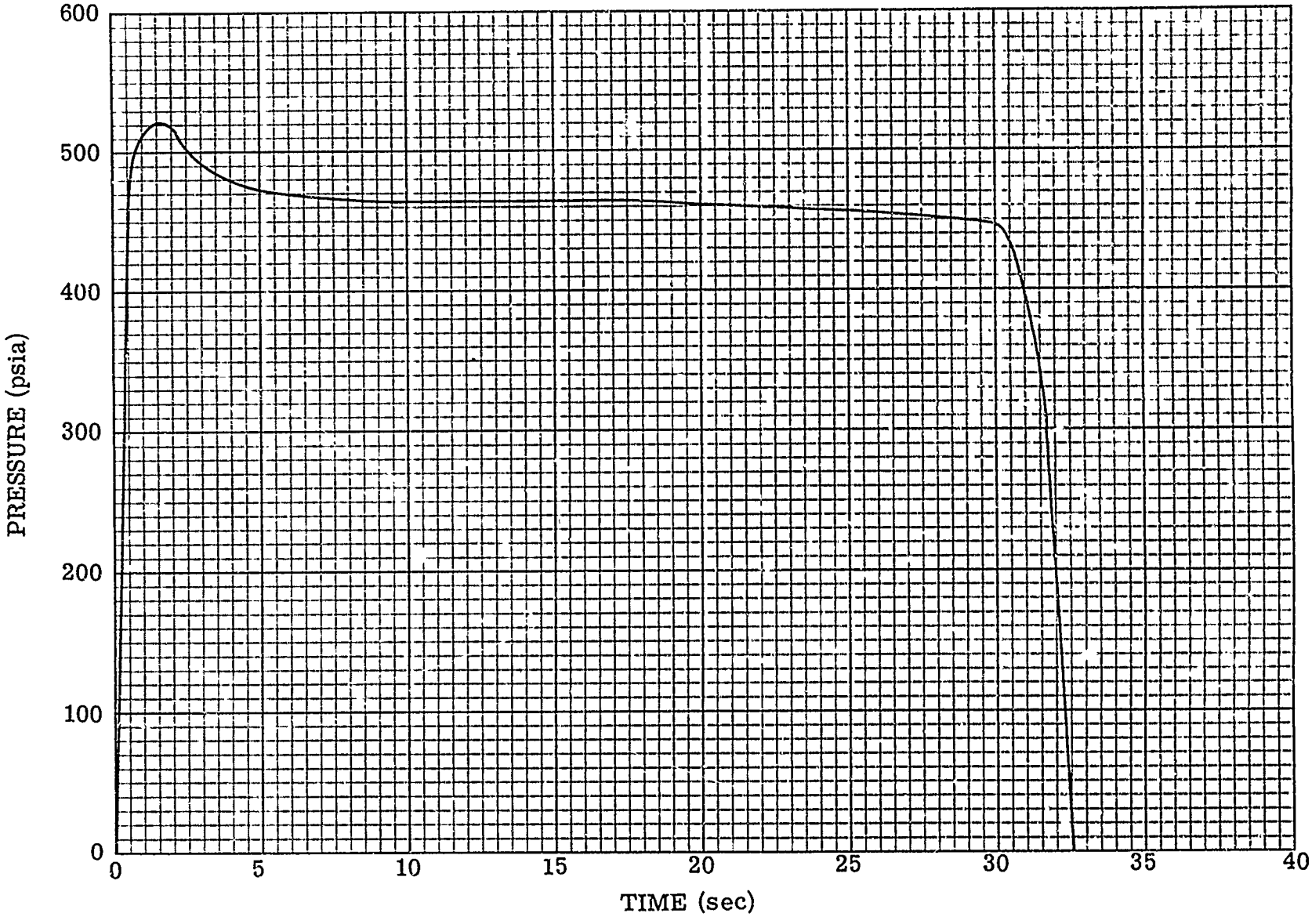


Figure 4. Motor Pressure Trace for Firing ASD-10.

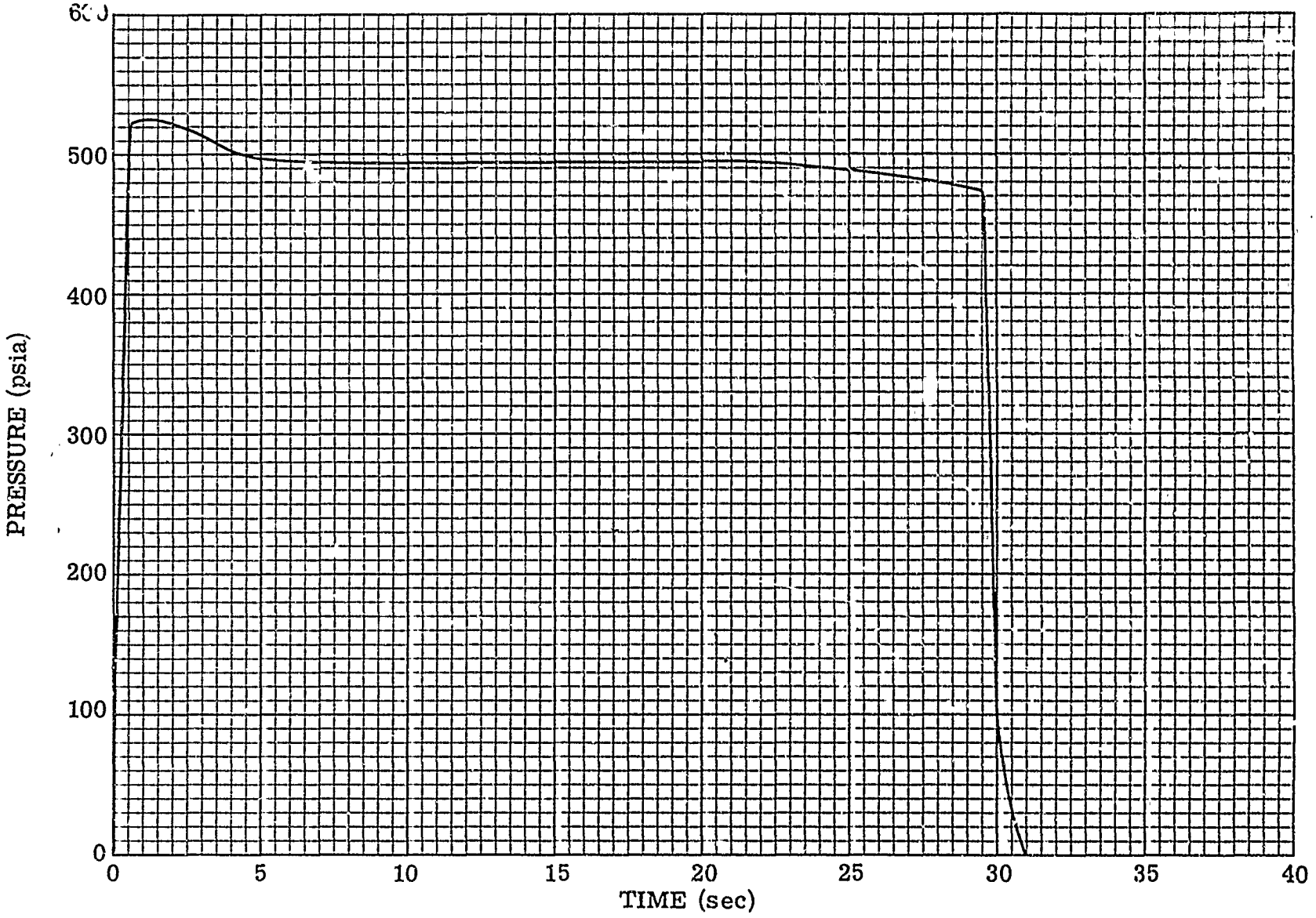


Figure 5. Motor Pressure Trace for Firing ASD-11.

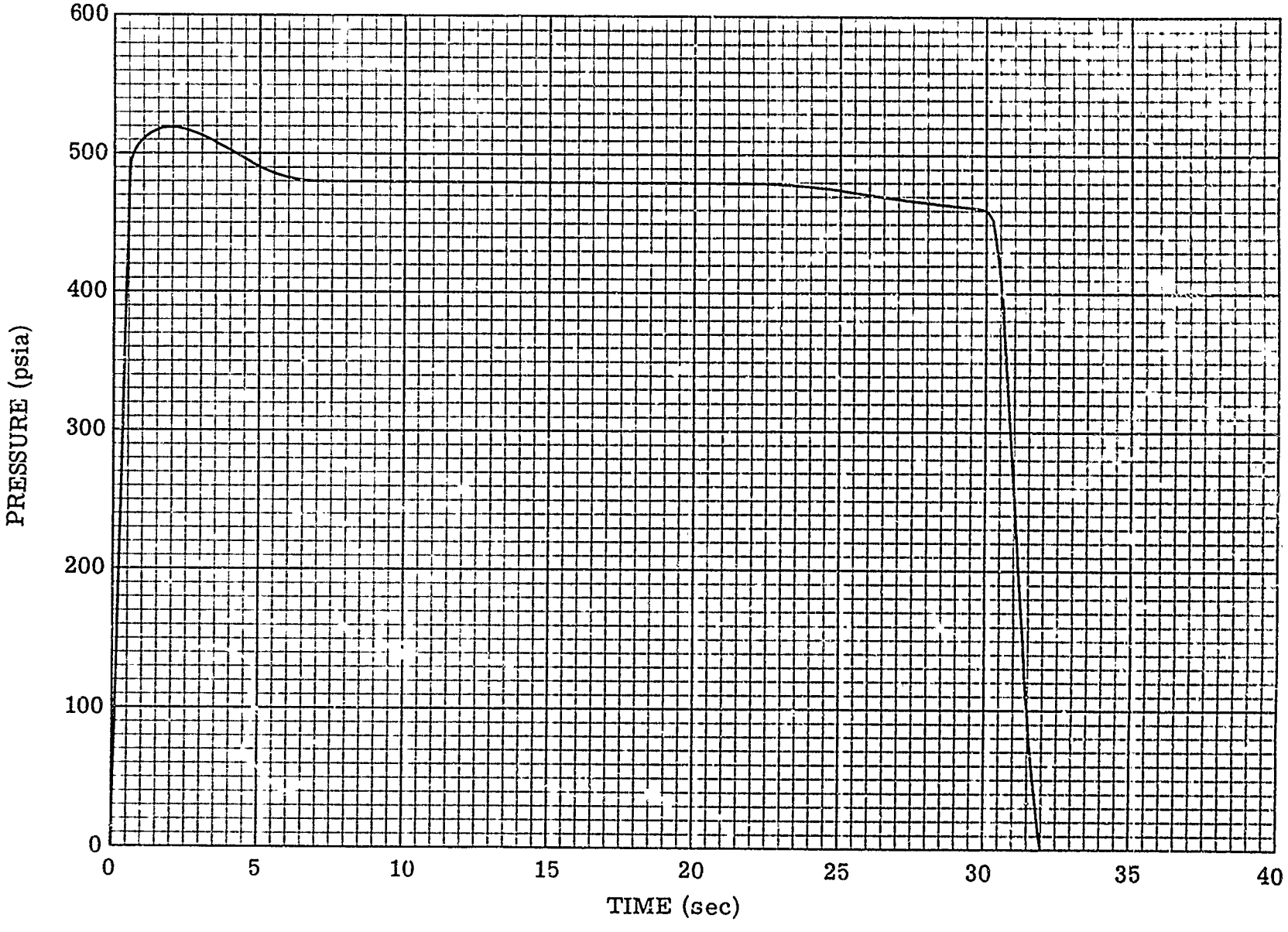


Figure 6. Motor Pressure Trace for Firing ASD-12.

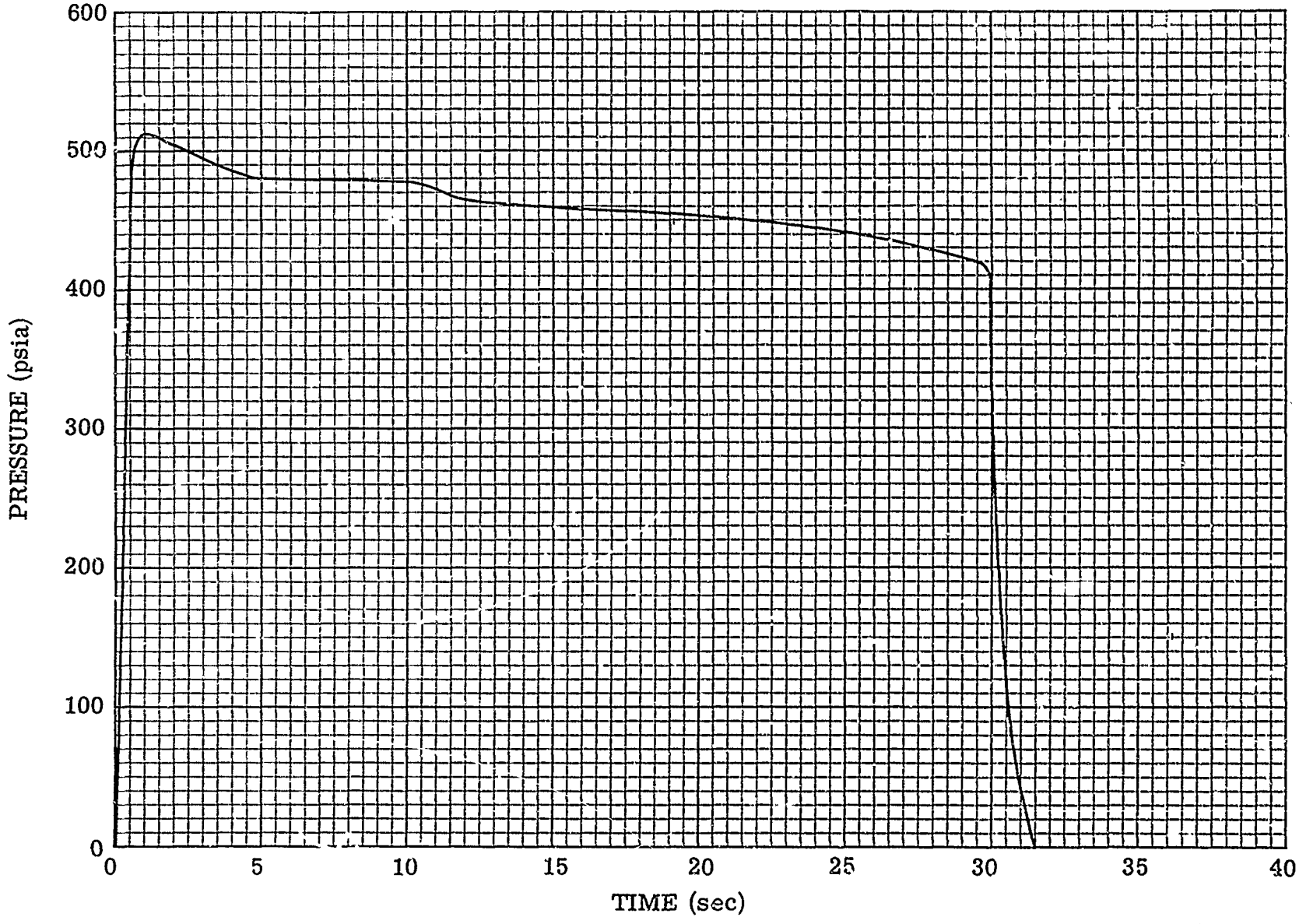


Figure 7. Motor Pressure Trace for Firing ASD-13.

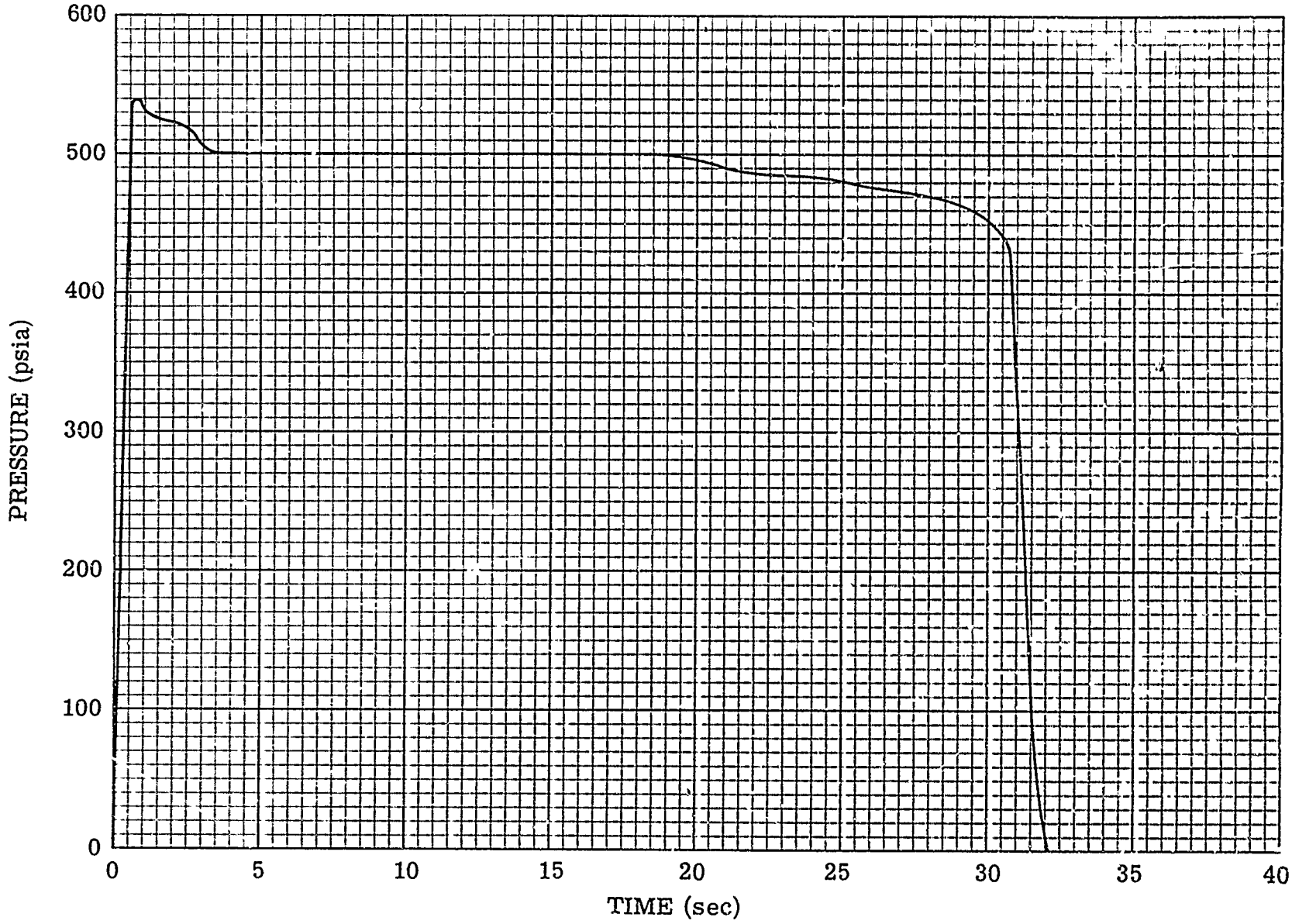


Figure 8. Motor Pressure Trace for Firing ASD-14.

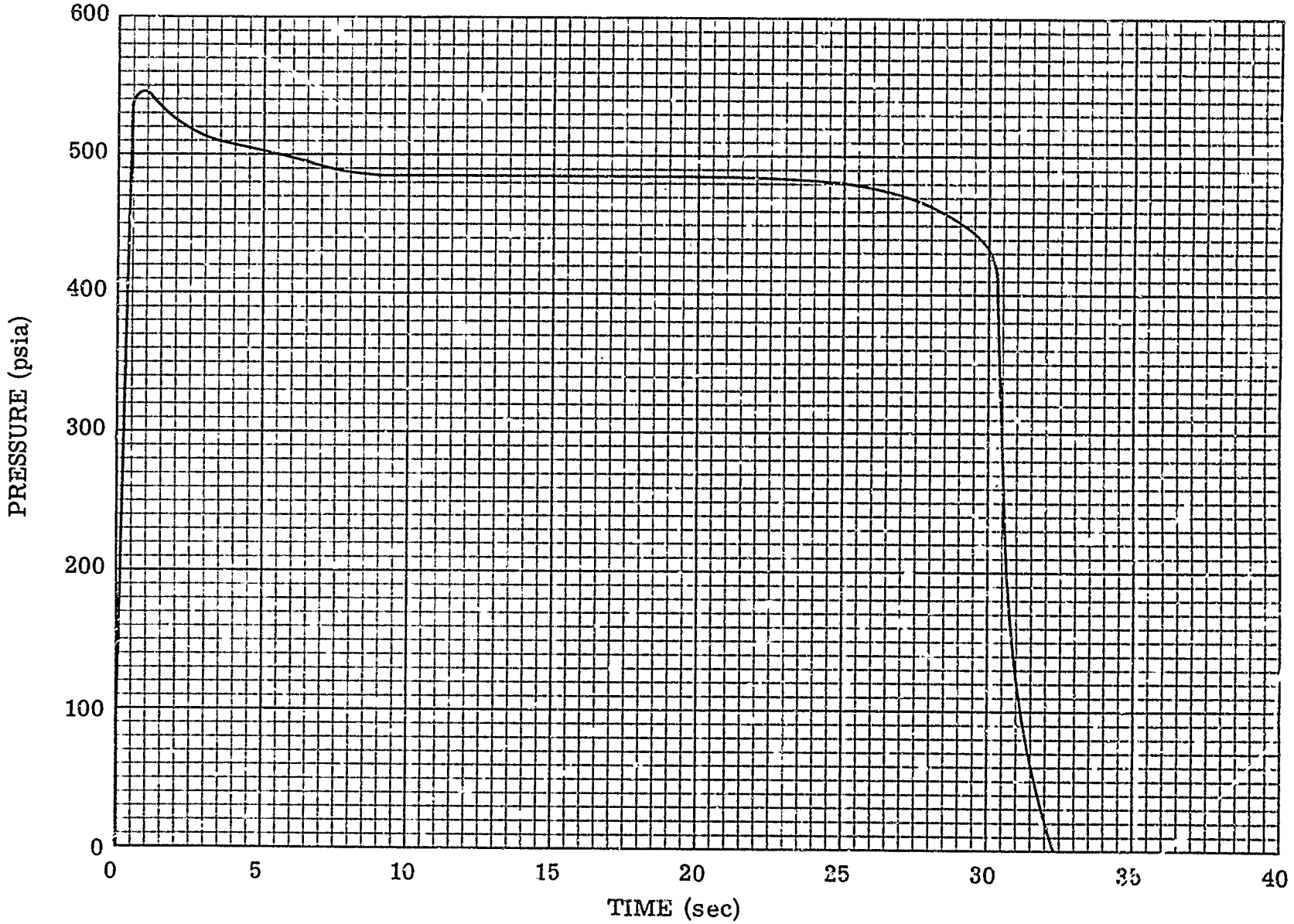


Figure 9. Motor Pressure Trace for Firing ASD-15.

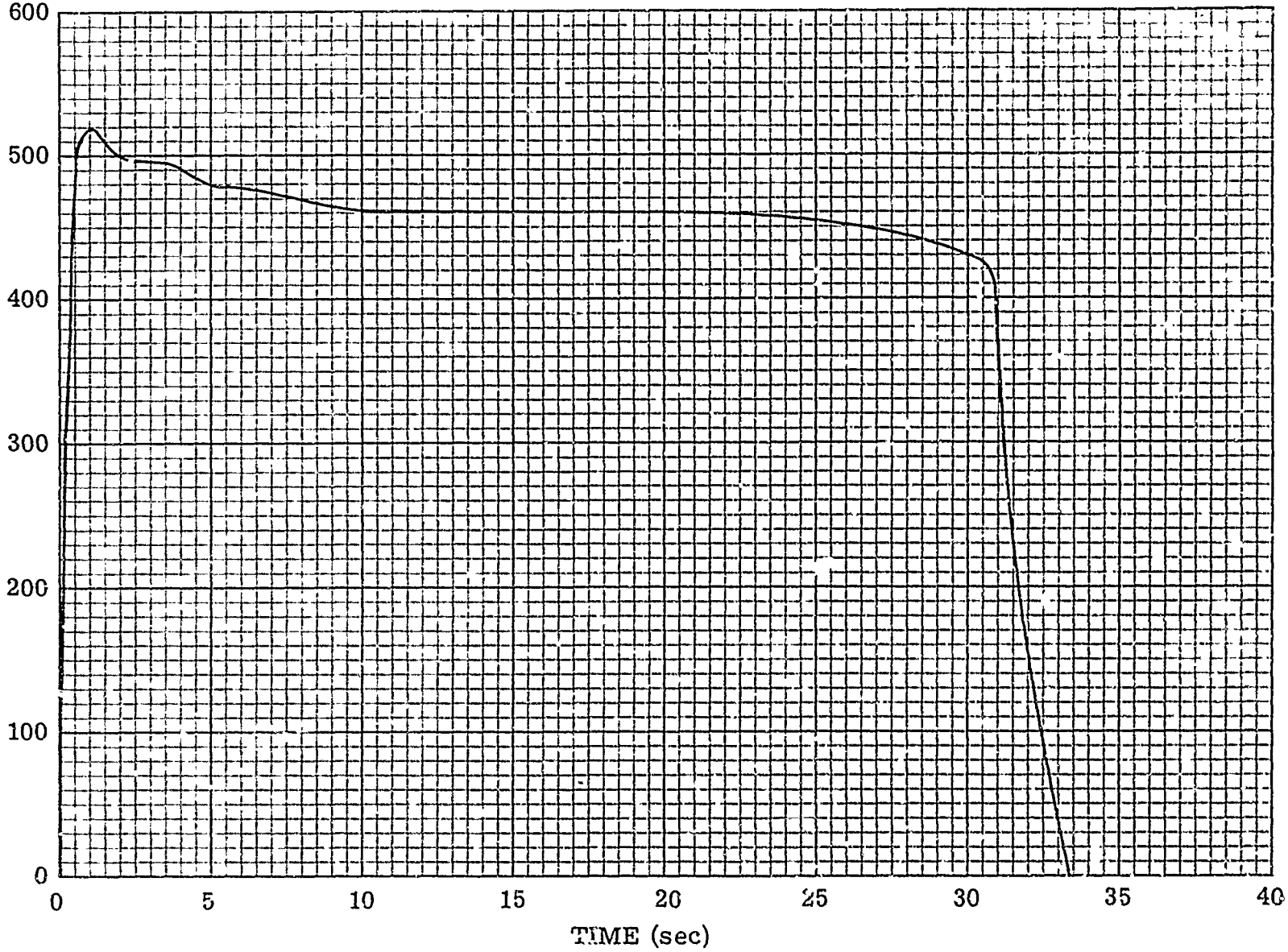


Figure 10. Motor Pressure Trace for Firing ASD-16.

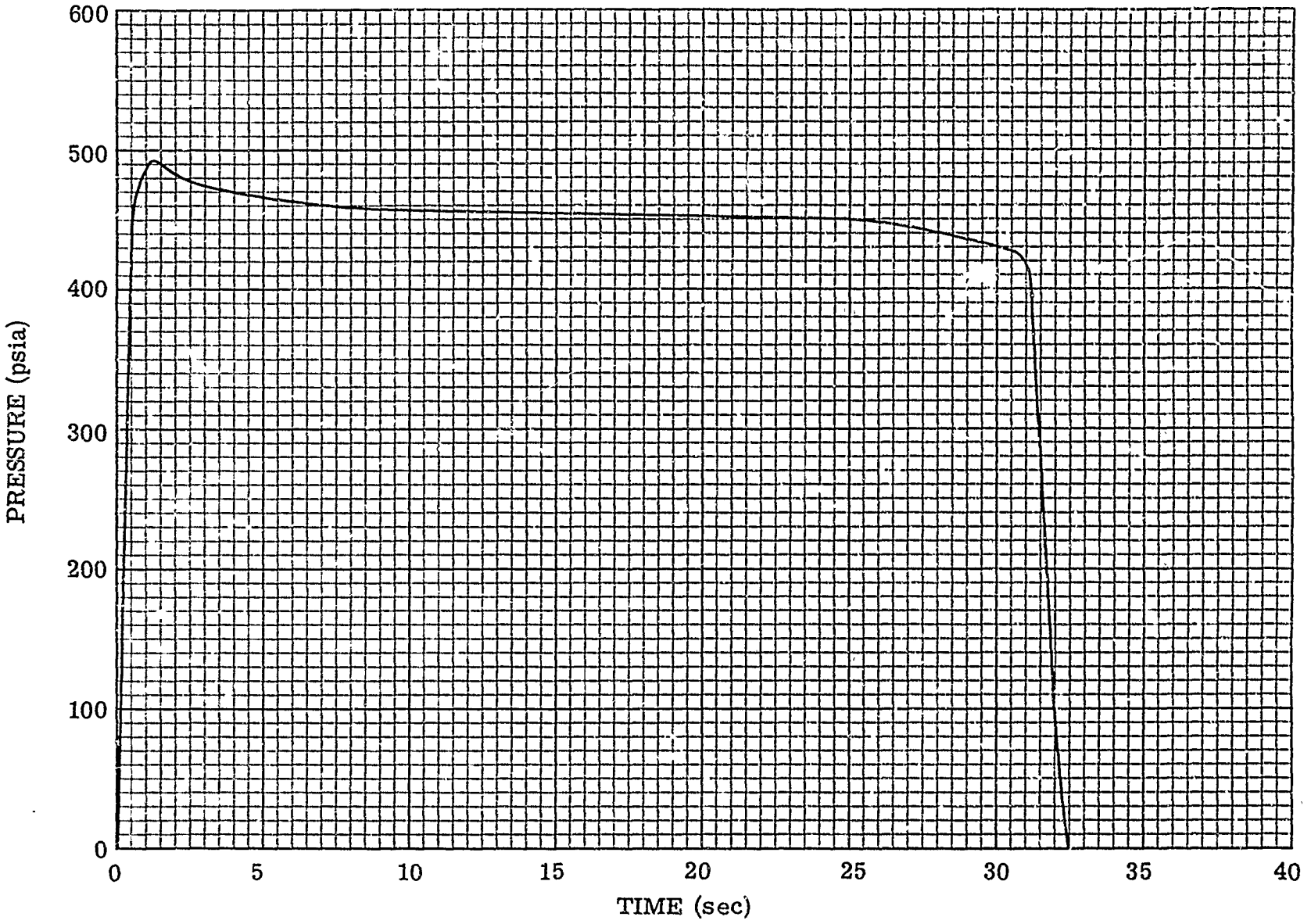


Figure 11. Motor Pressure Trace for Firing ASD-17.

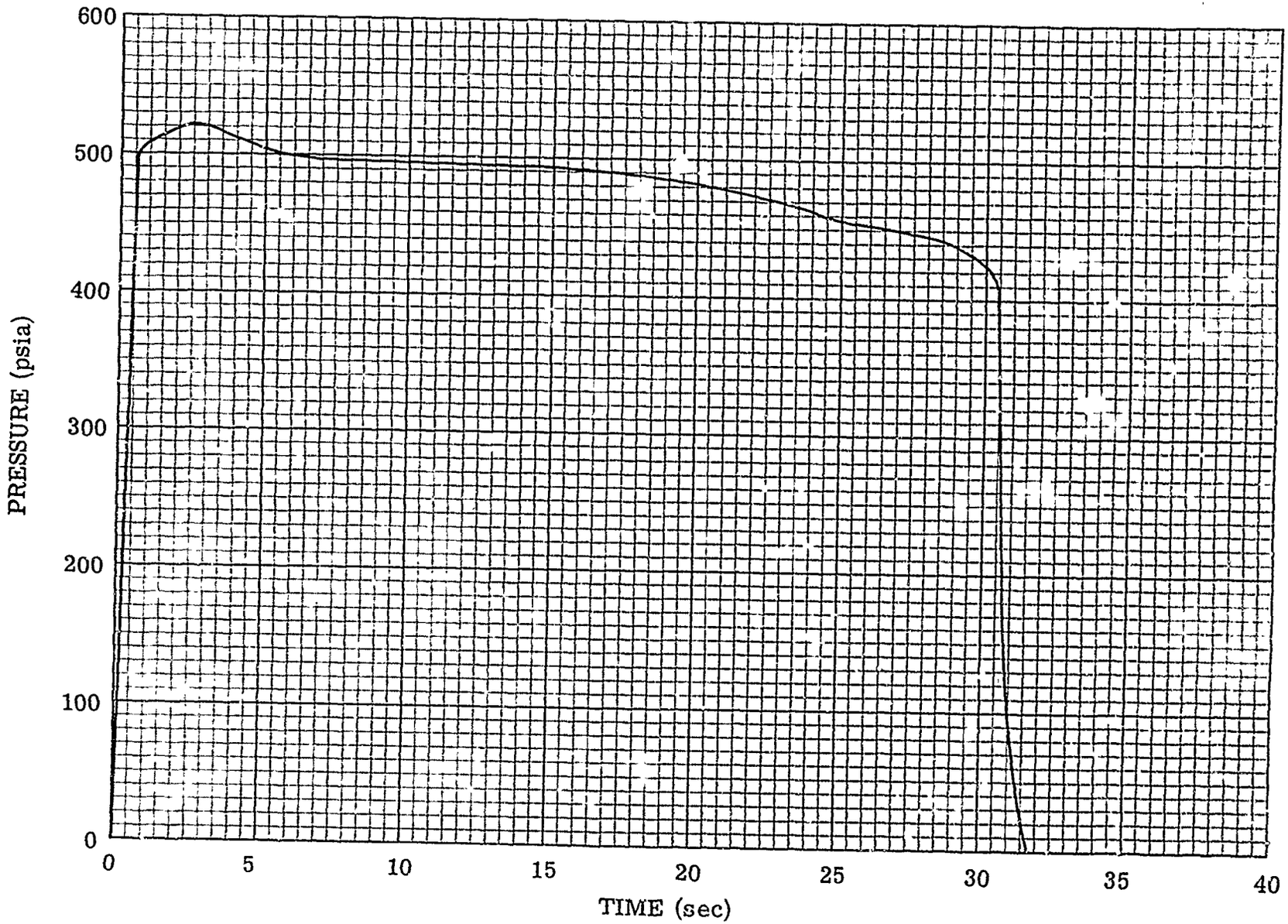


Figure 12. Motor Pressure Trace for Firing ASD-18.

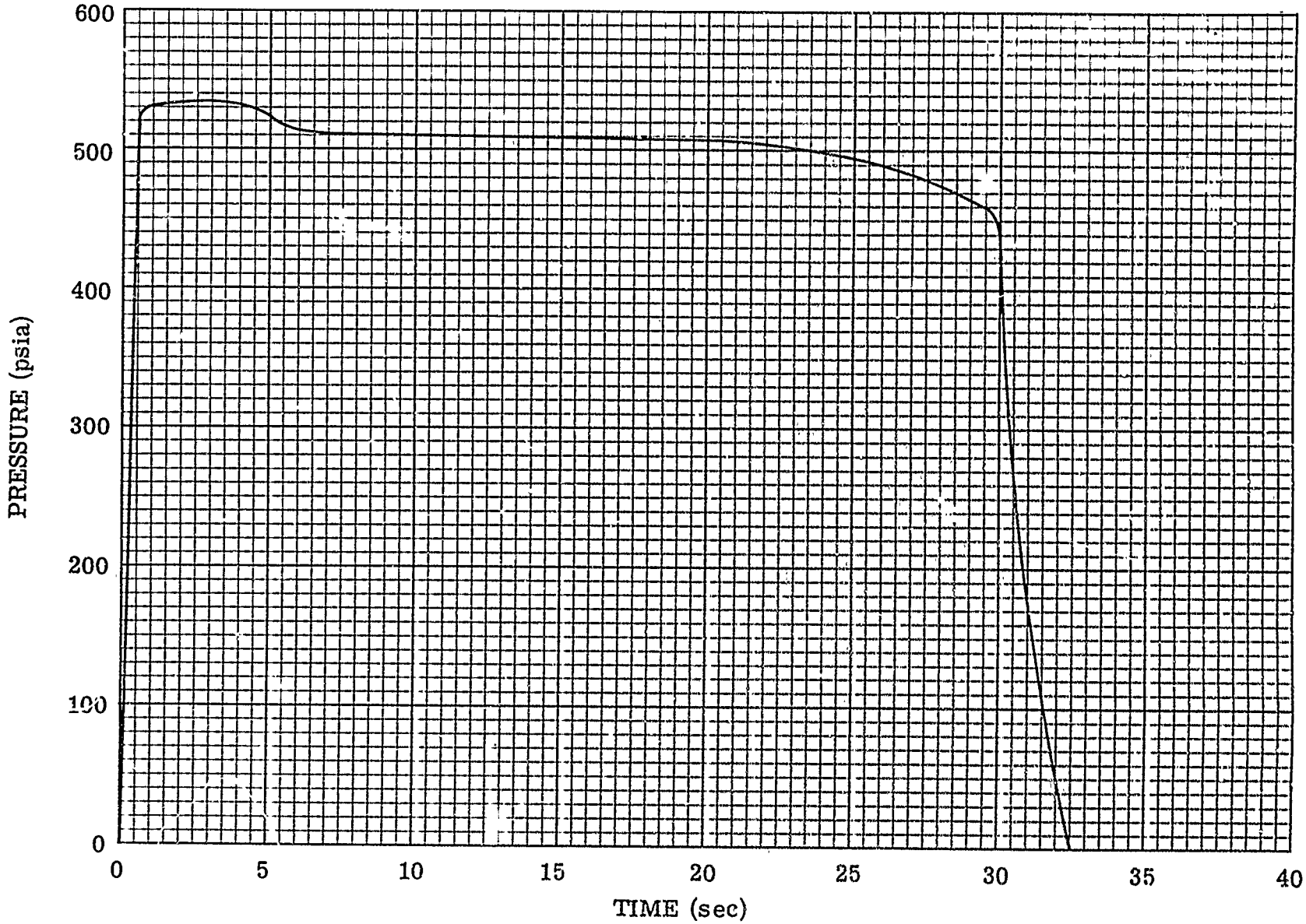


Figure 13. Motor Pressure Trace for Firing ASD-19.

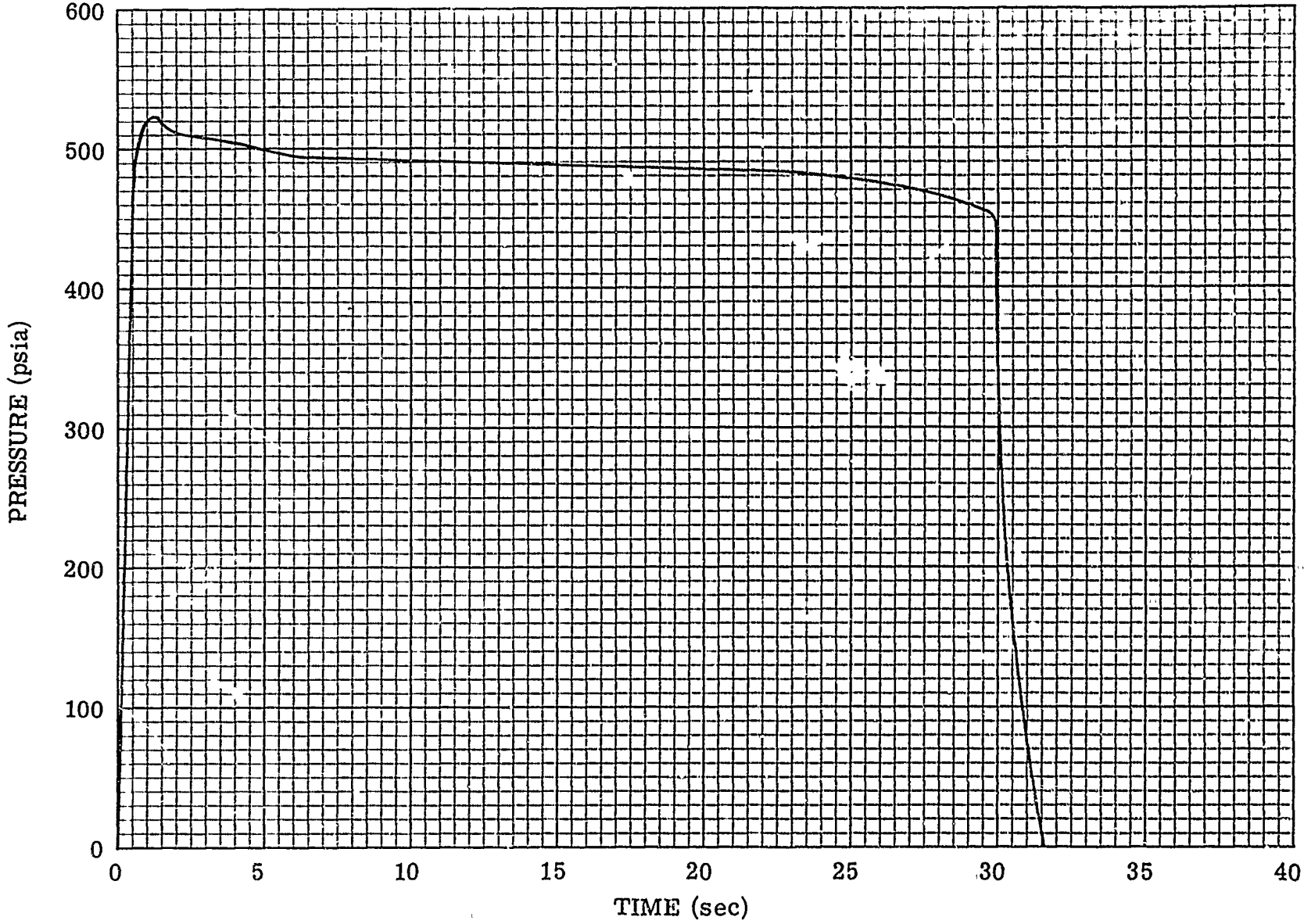


Figure 14. Motor Pressure Trace for Firing ASD-20.

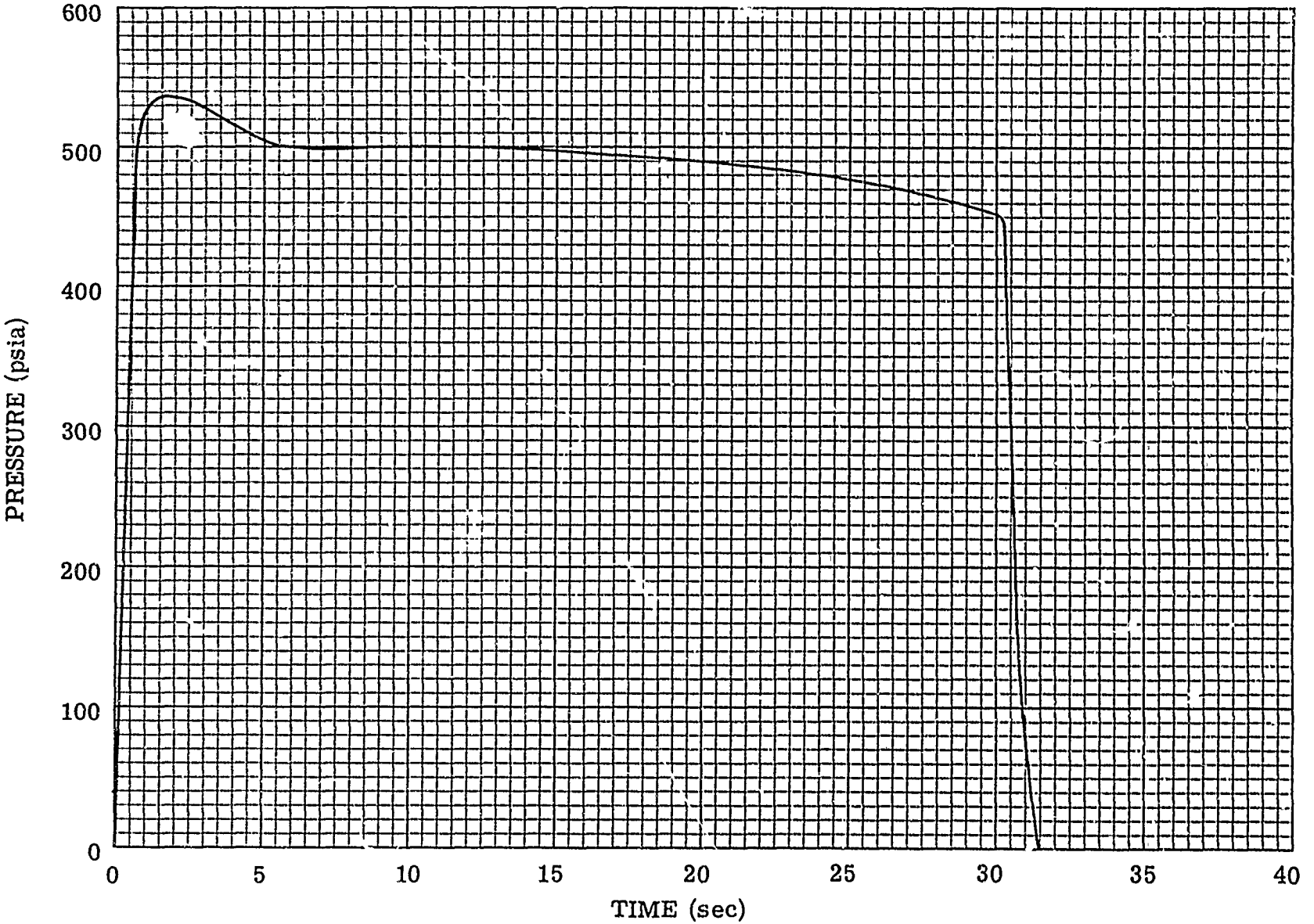
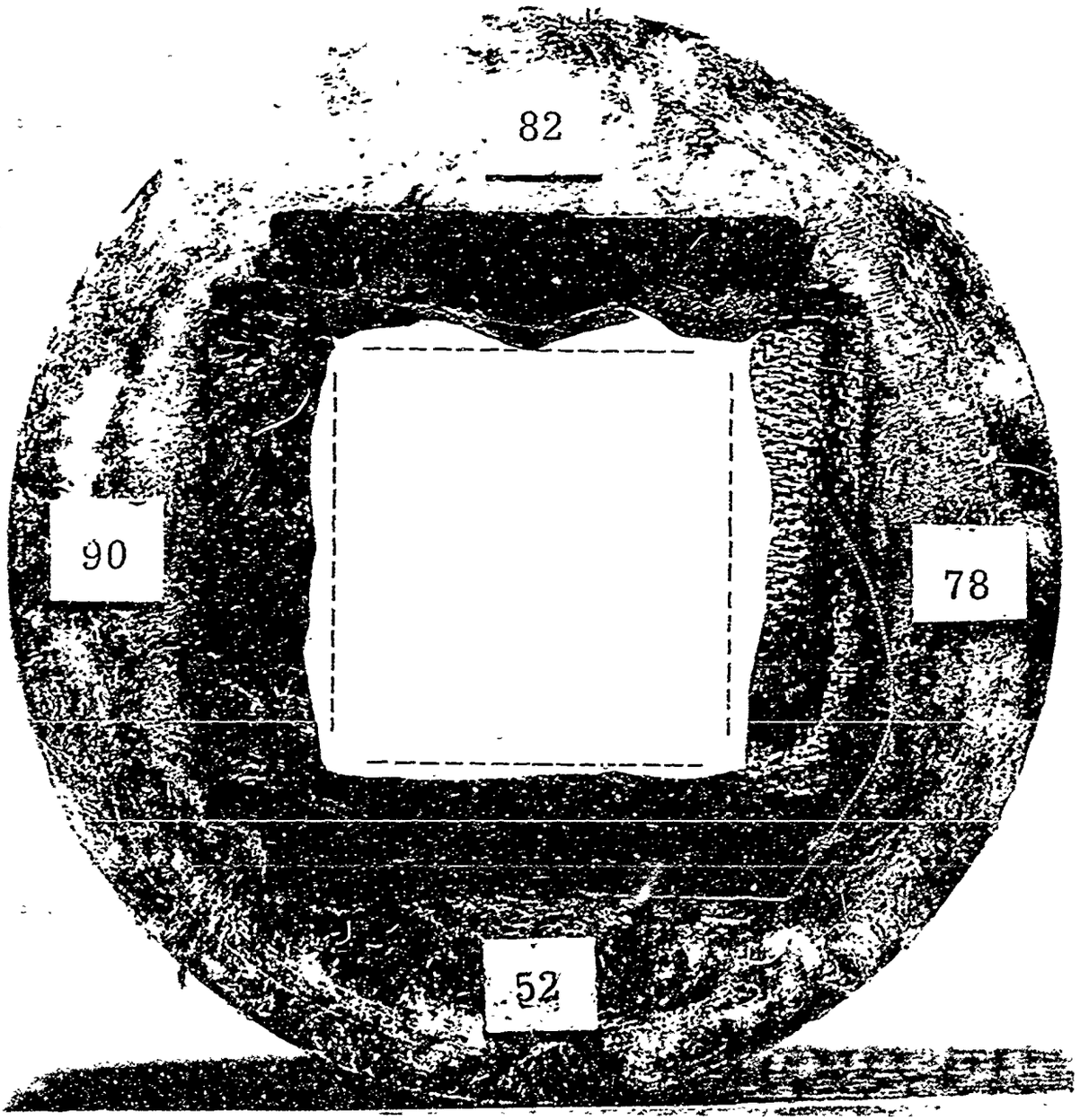
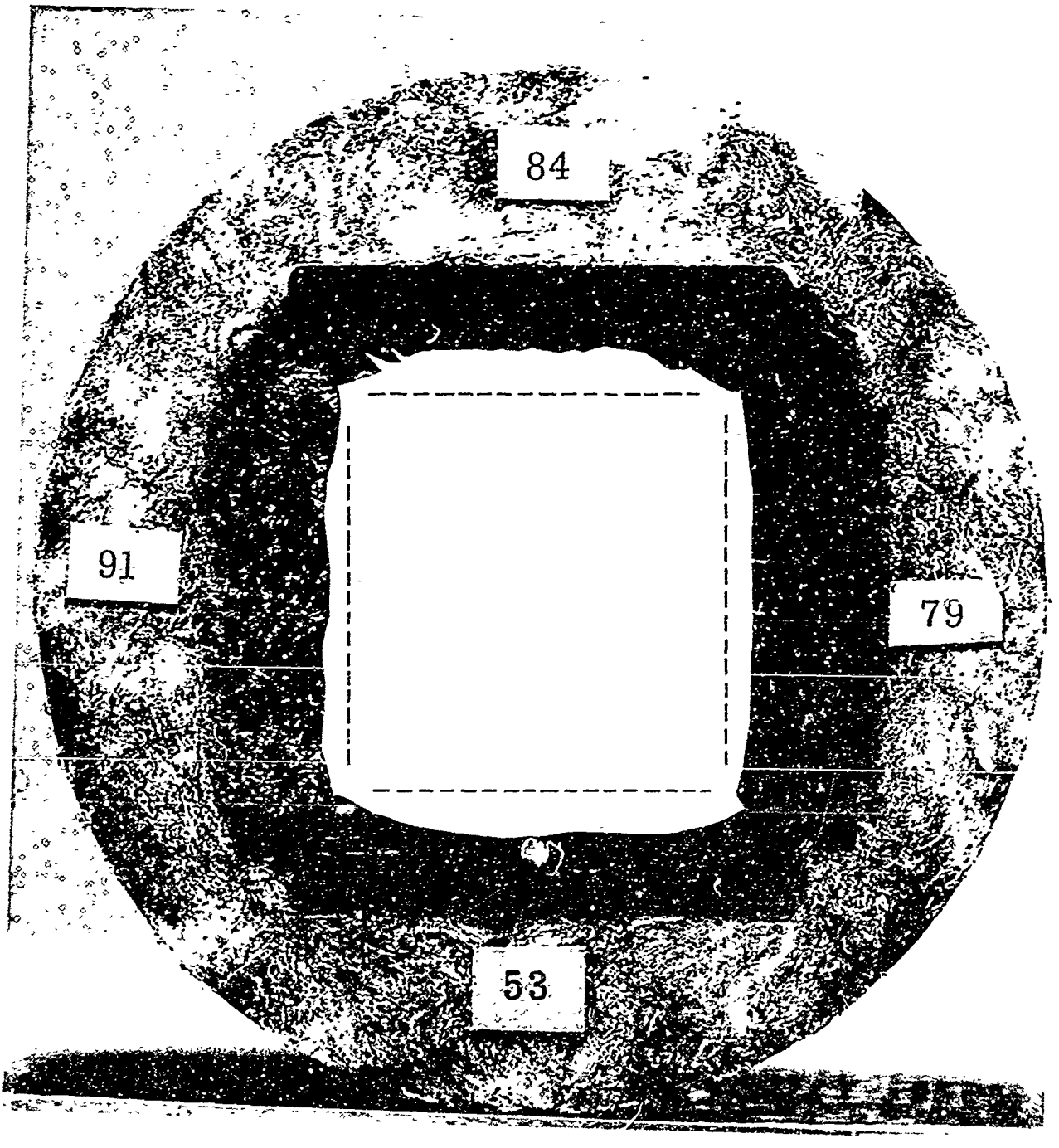


Figure 15. Motor Pressure Trace for Firing ASD-21.



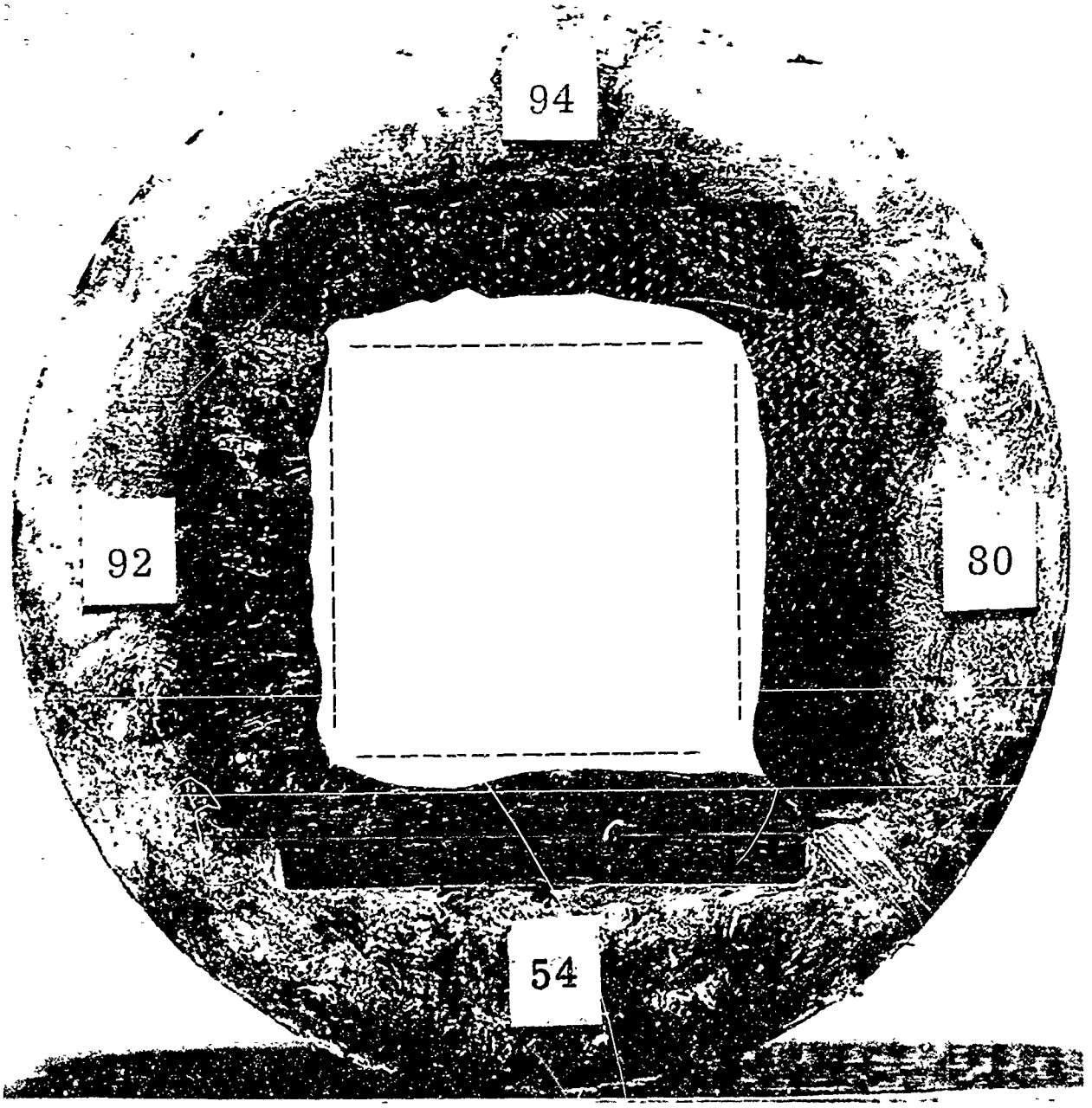
82 - Phenolic/Pluton B cloth (parallel)
78 - Phenolic/carbon cloth (edge)
52 - Phenolic/carbon cloth (parallel)
90 - Phenolic/carbon cloth (chopped squares)

Figure 16. Specimens After Test ASD-9, Nozzle End Section.



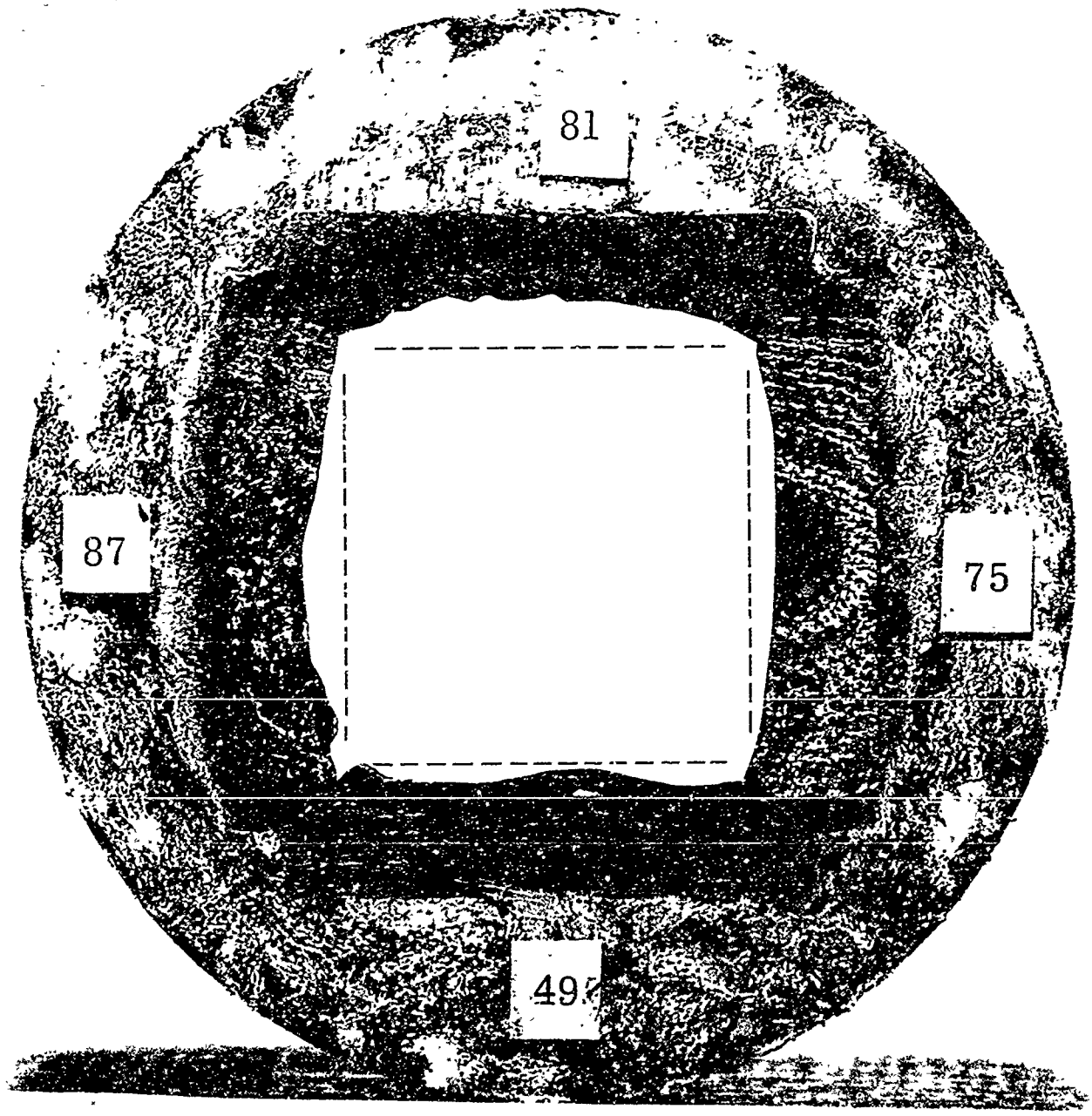
84 - Phenolic/Pluton H cloth (parallel)
79 - Phenolic/carbon cloth (edge)
53 - Phenolic/carbon cloth (parallel)
91 - Phenolic/carbon cloth (chopped squares)

Figure 17. Specimens After Test ASD-9, Center Section.



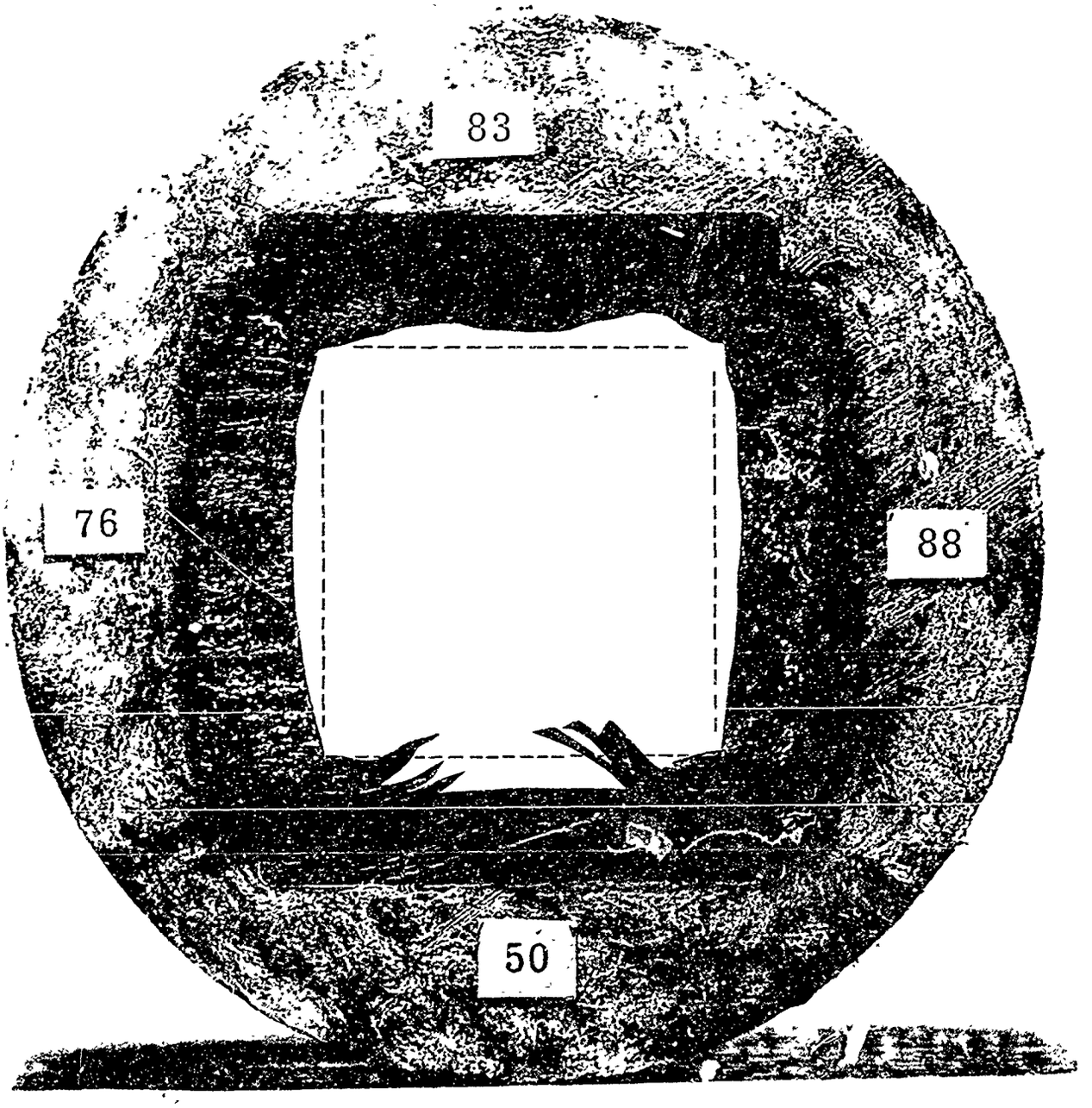
94 - Polyphenylene/carbon cloth (edge)
80 - Phenolic/carbon cloth (edge)
54 - Phenolic/carbon cloth (parallel)
92 - Phenolic/carbon cloth (chopped squares)

Figure 18. Specimens After Test ASD-9, Motor End Section.



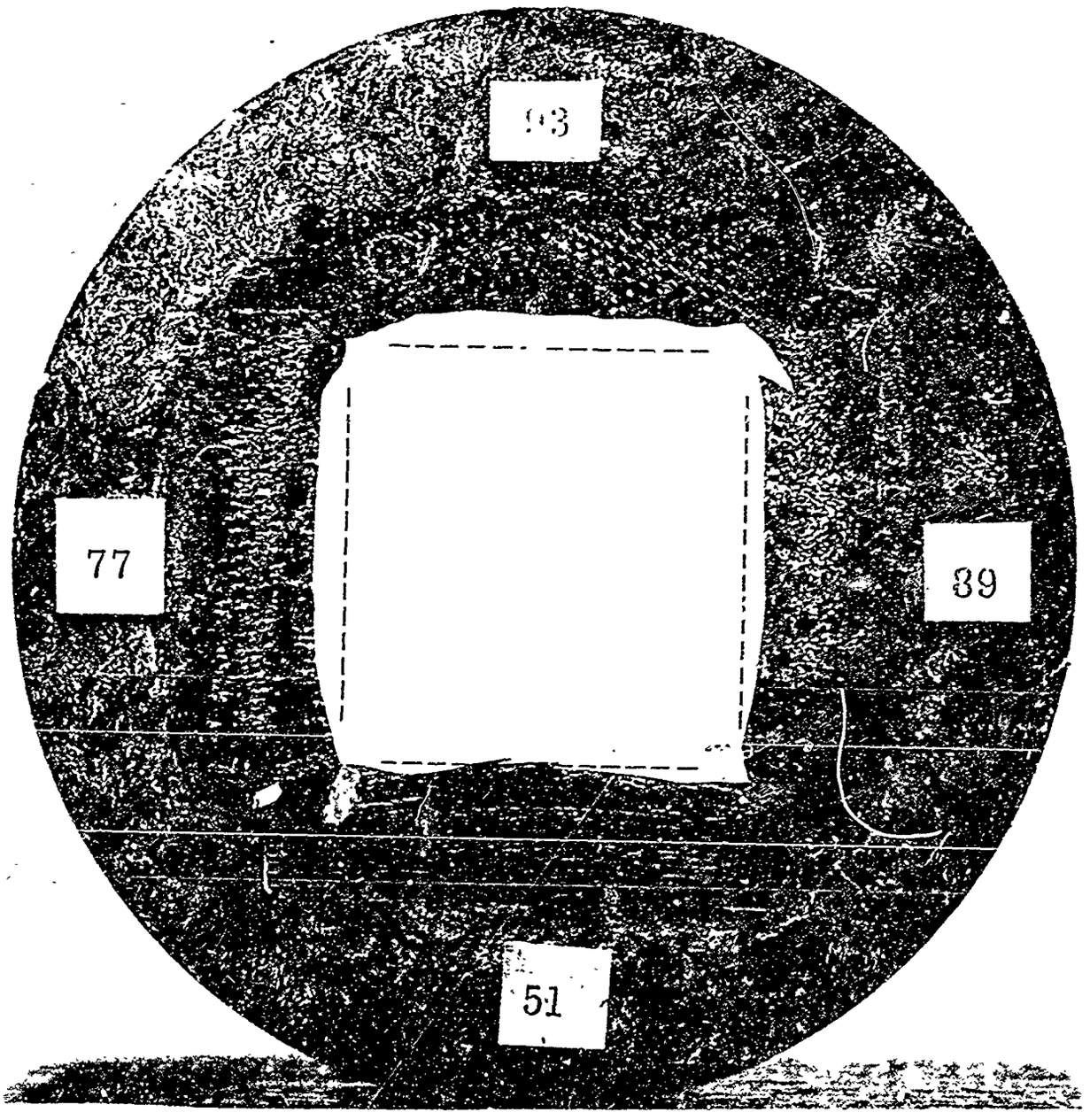
81 - Phenolic/Pluton B cloth (parallel)
75 - Phenolic/carbon cloth (edge)
49 - Phenolic/carbon cloth (parallel)
87 - Phenolic/carbon cloth (chopped squares)

Figure 19. Specimens After Test ASD-10, Nozzle End Section.



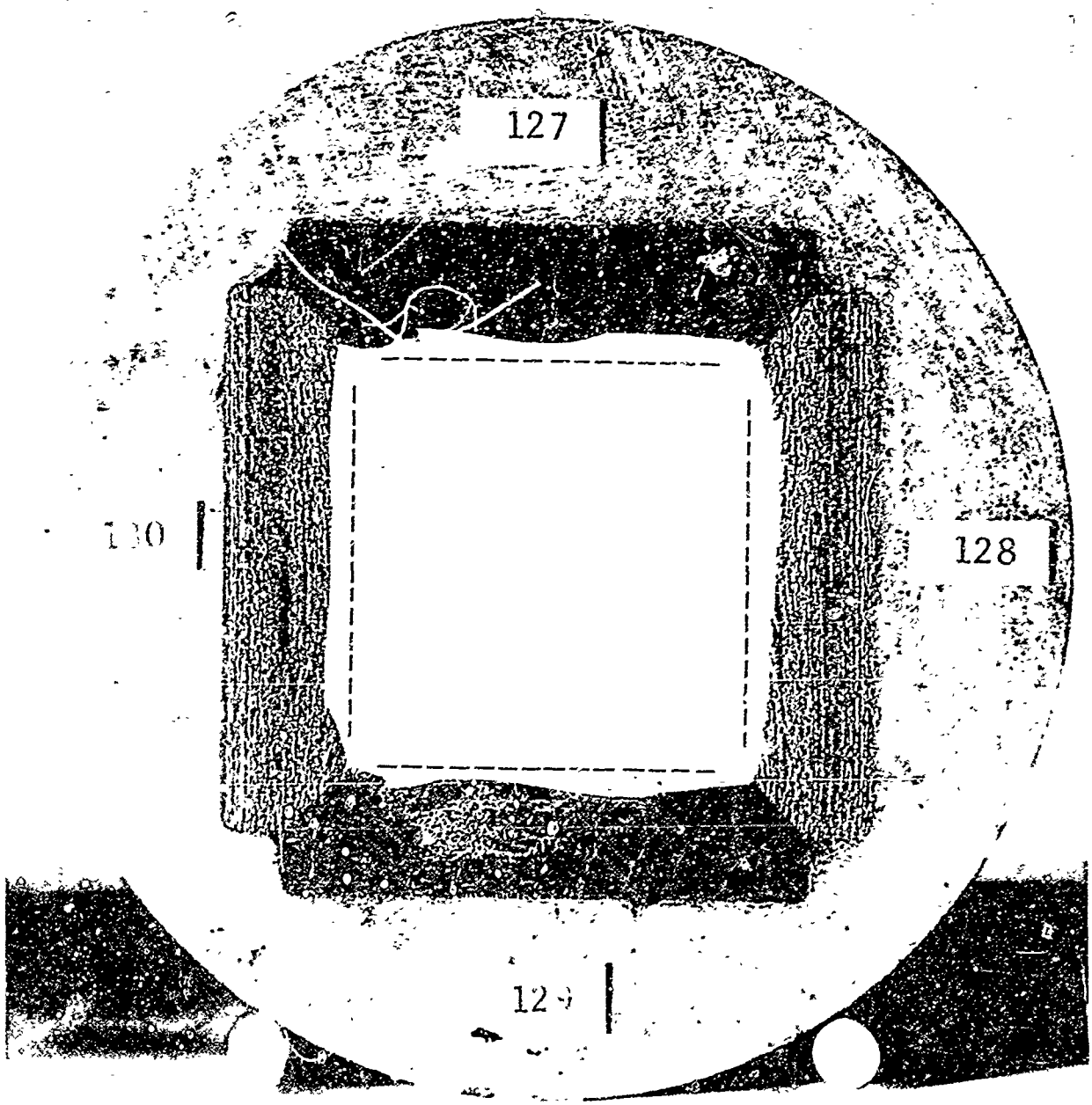
83 - Phenolic/Pluton H cloth (parallel)
76 - Phenolic/carbon cloth (edge)
50 - Phenolic/carbon cloth (parallel)
88 - Phenolic/carbon cloth (chopped squares)

Figure 20. Specimens After Test ASD-10, Center Section.



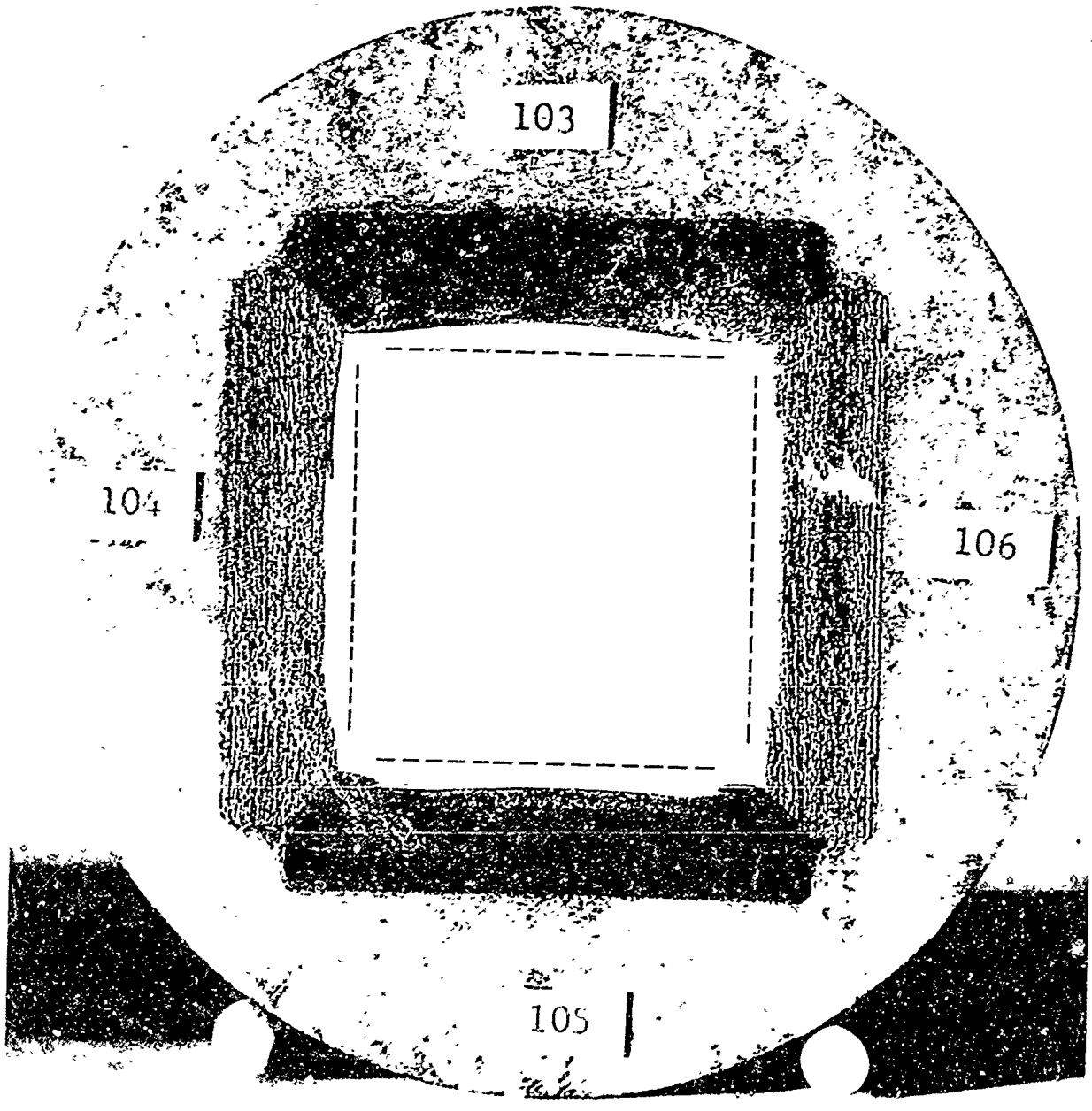
93 - Polyphenylene/carbon cloth (edge)
77 - Phenolic/carbon cloth (edge)
51 - Phenolic/carbon cloth (parallel)
89 - Phenolic/carbon cloth (chopped squares)

Figure 21. Specimens After Test ASD-10, Motor End Section.



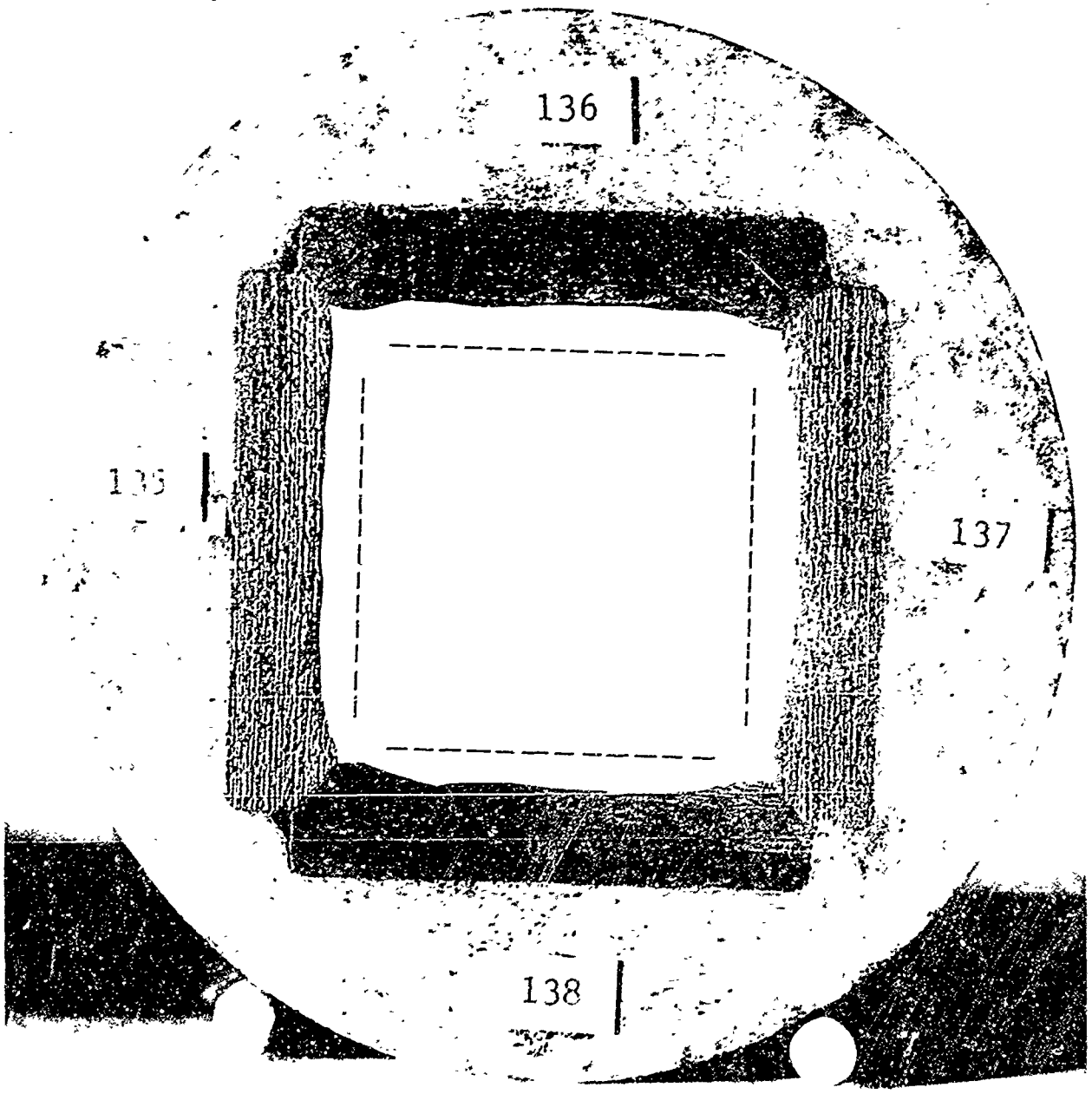
Phenylphenol phenol formaldehyde/graphite cloth (parallel)

Figure 22. Specimens After Test ASD-11, Nozzle End Section.



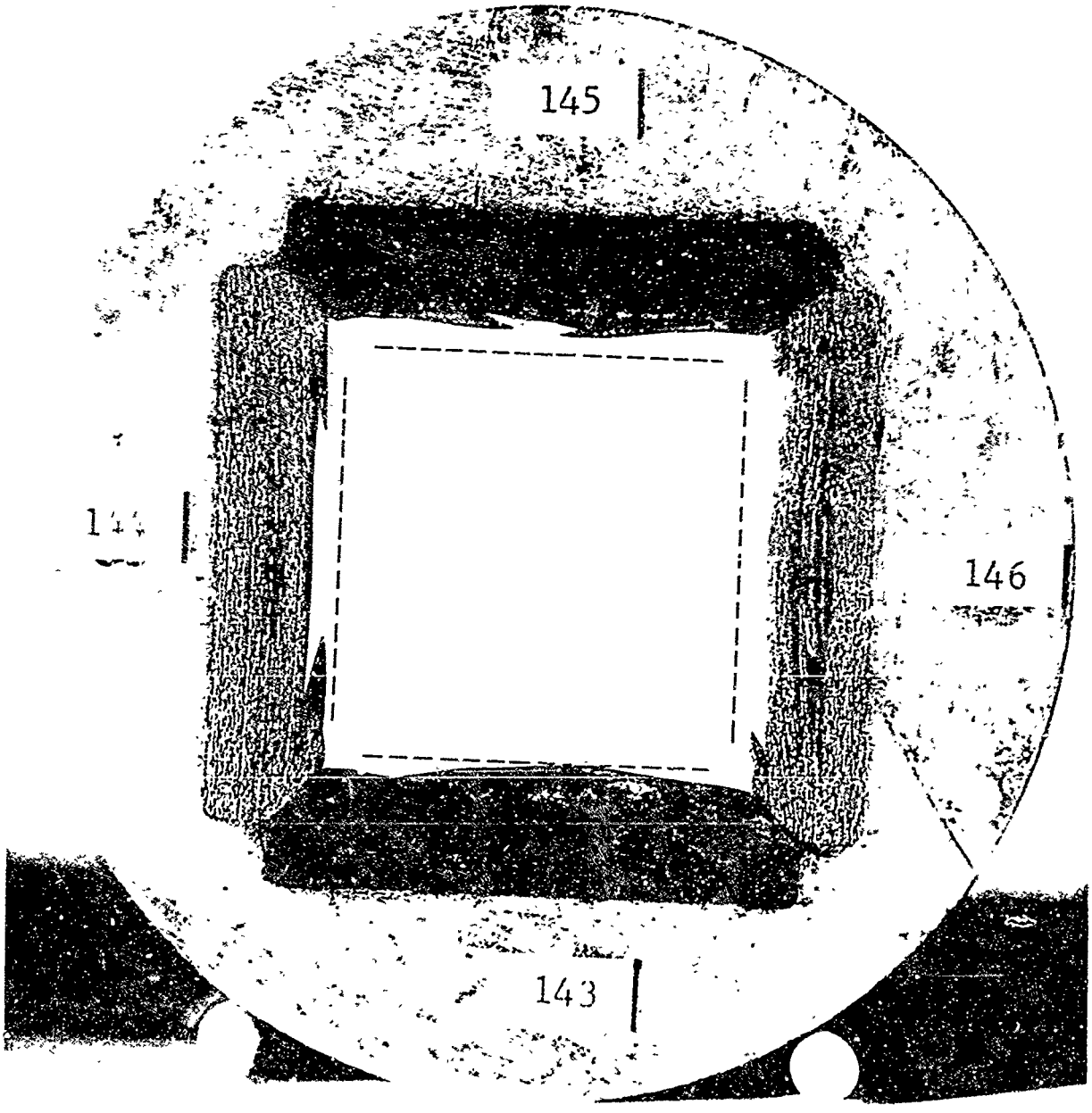
Phenolic/graphite cloth (parallel)

Figure 23. Specimens After Test ASD-11, Center Section.



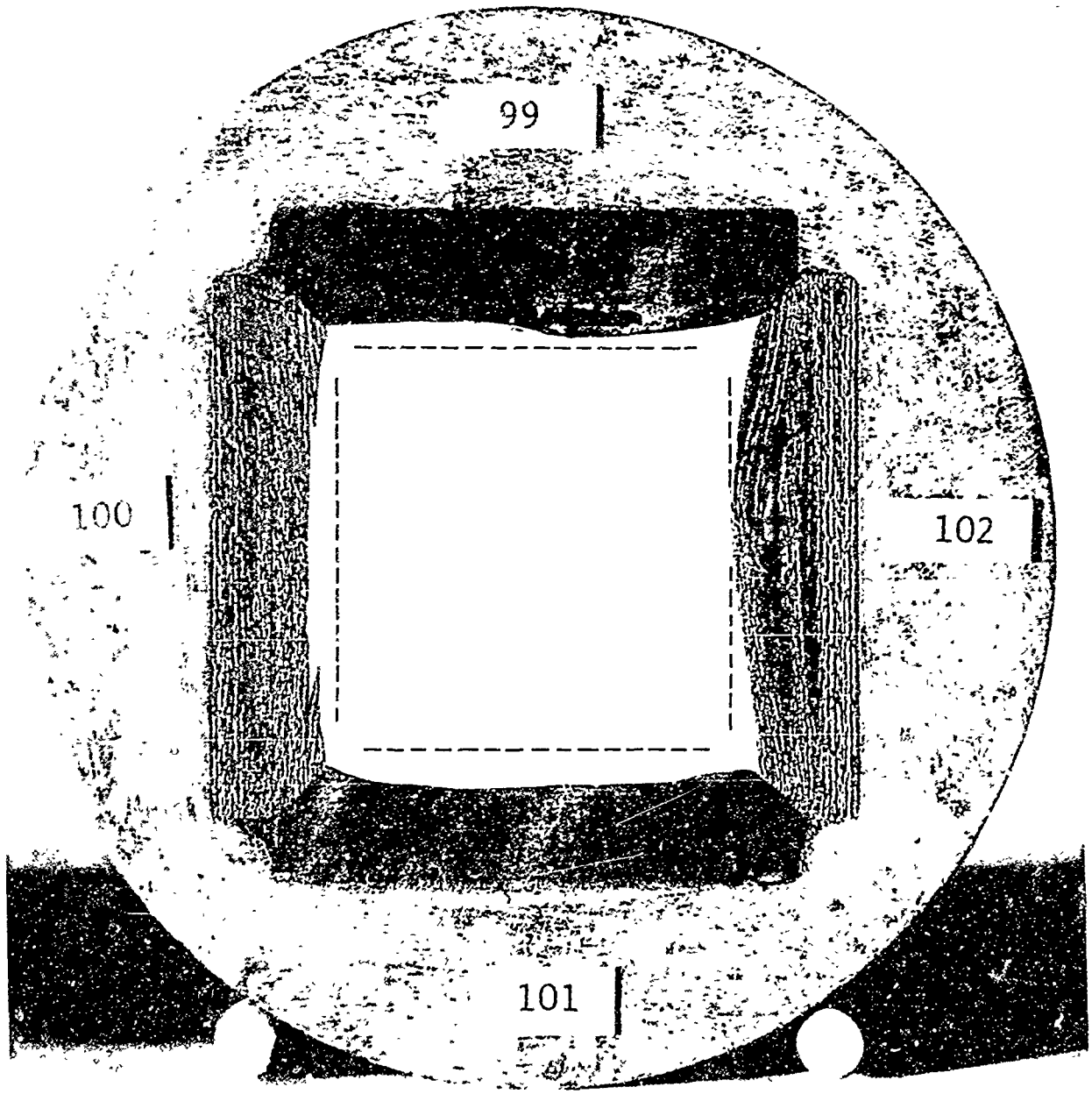
Polyimide/graphite cloth (parallel)

Figure 24. Specimens After Test ASD-11, Motor End Section.



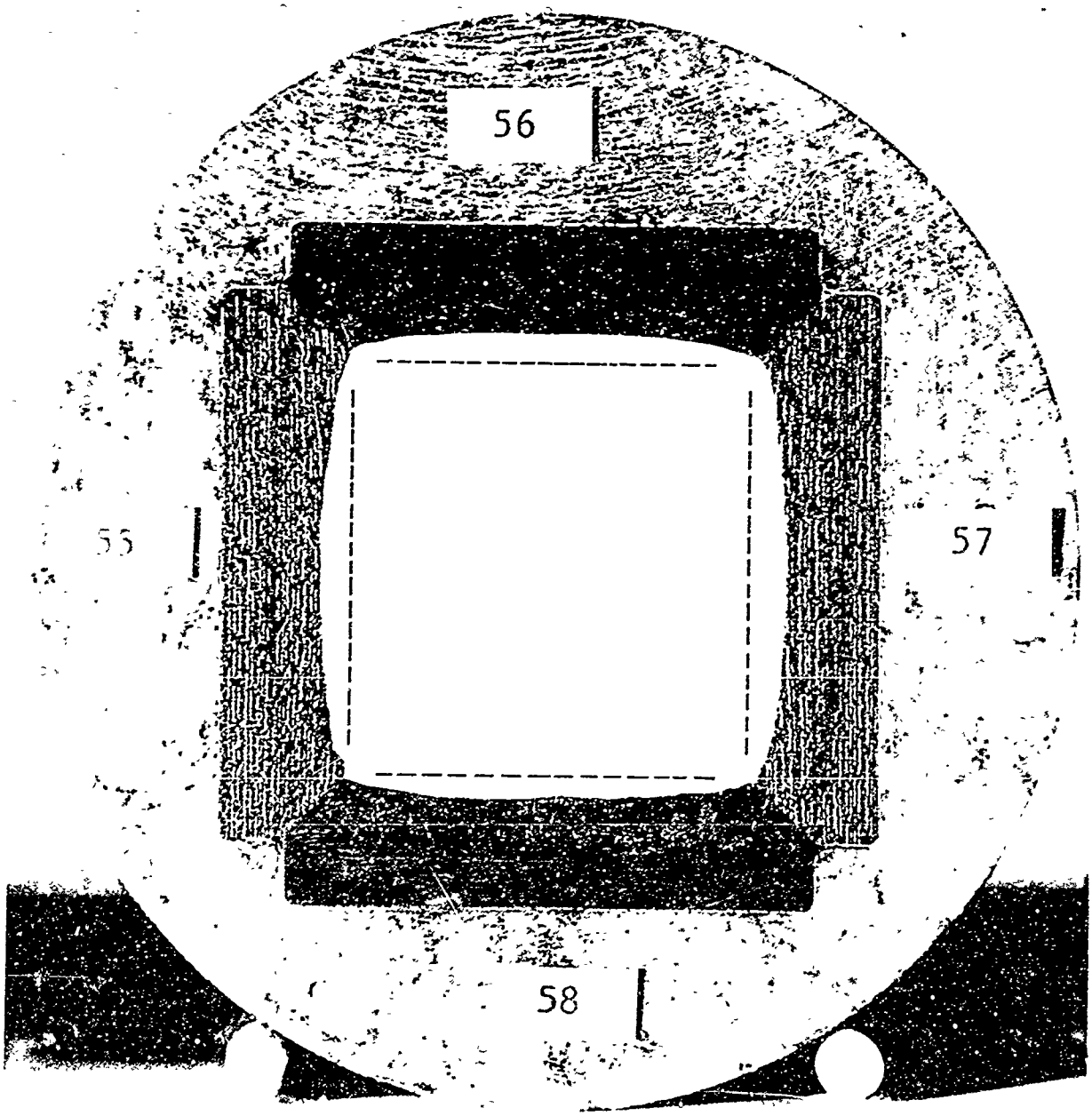
2,7-Dihydroxynaphthalene phenolic/graphite cloth (parallel)

Figure 25. Specimens After Test ASD-12, Noz .le End Section.



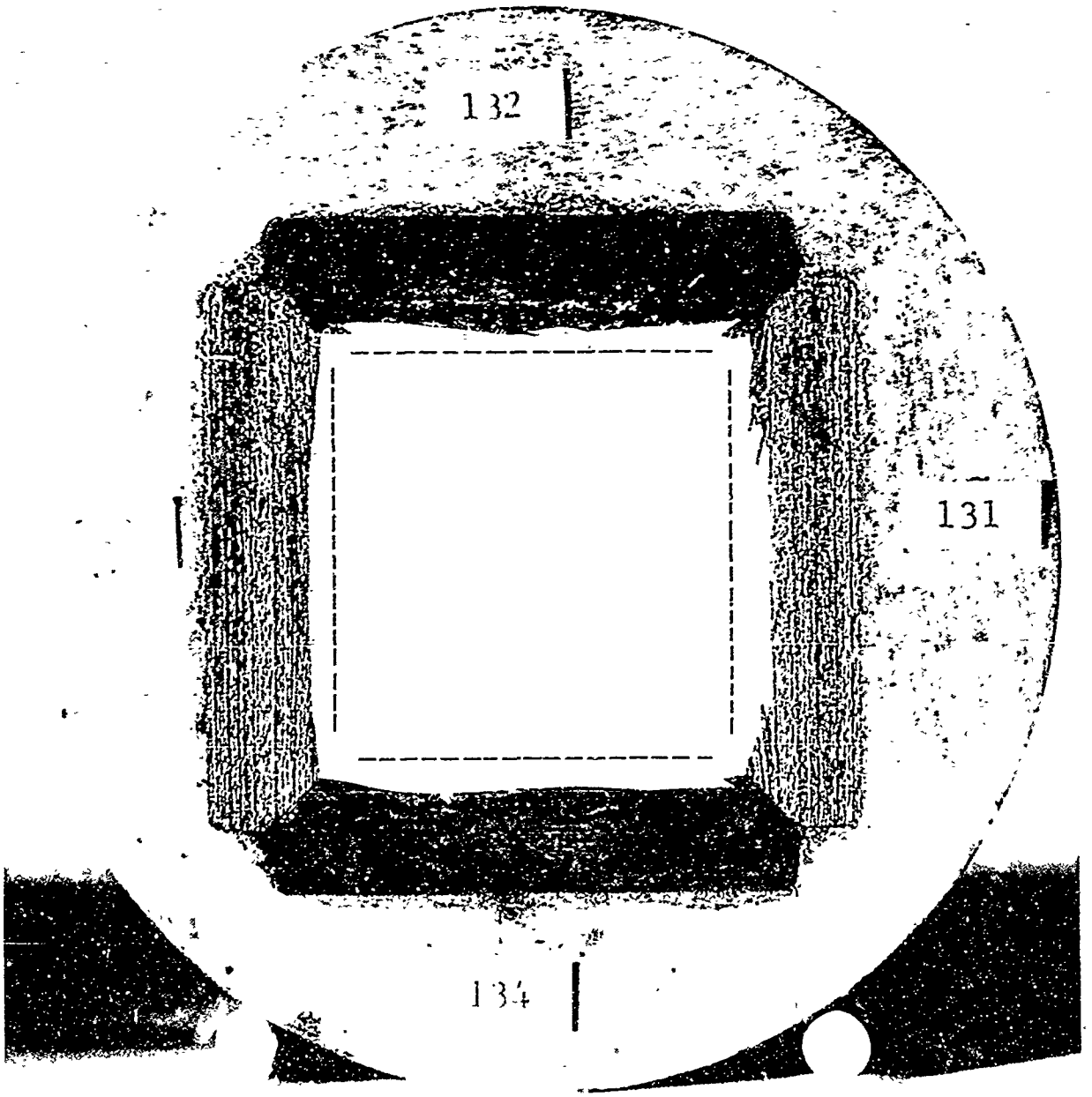
Phenolic/ graphite cloth (parallel)

Figure 26. Specimens After Test ASD-12, Center Section.



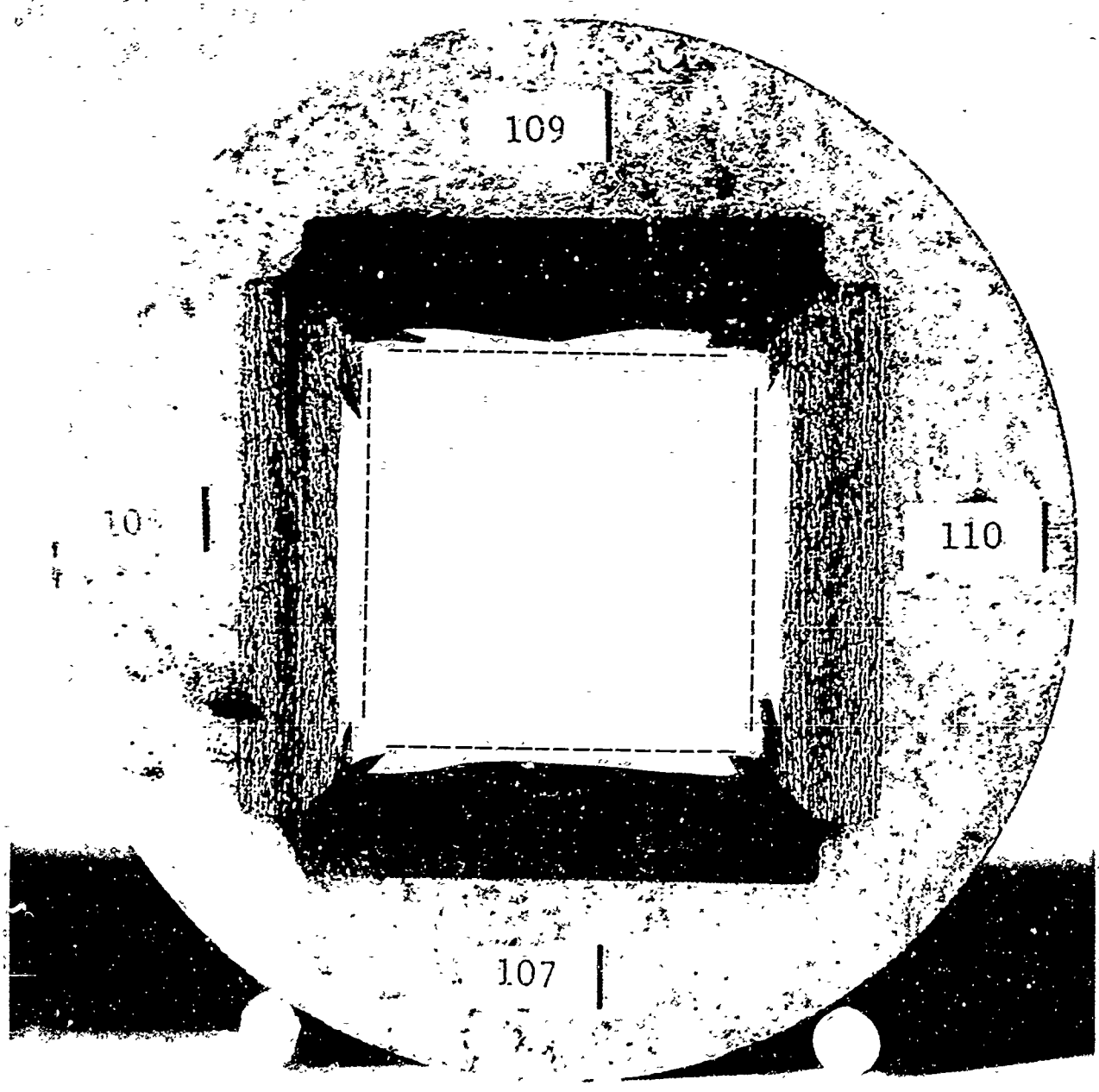
Phenolic/carbon cloth (parallel)

Figure 27. Spécimens After Test ASD-12, Motor End Section.



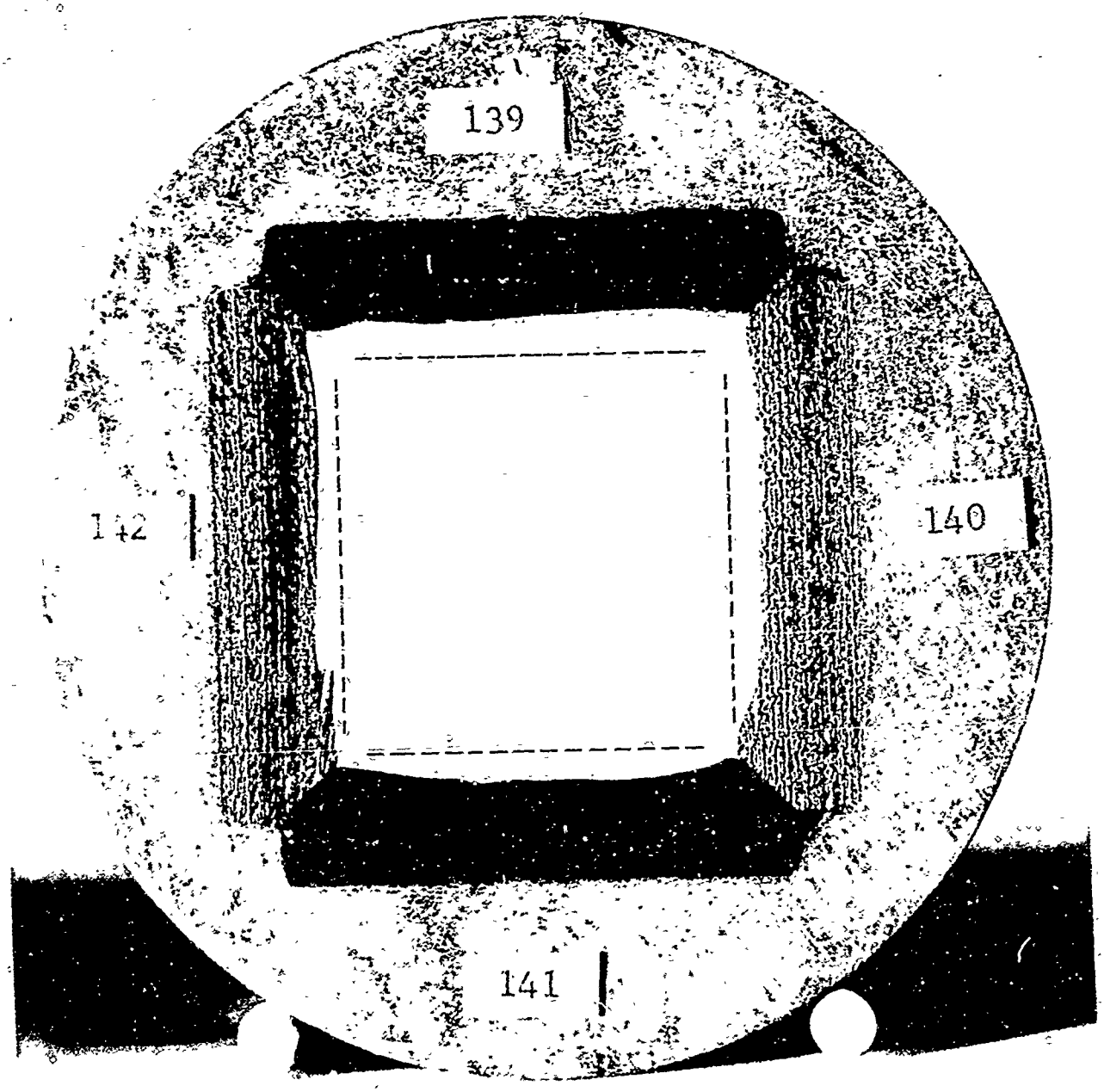
Diphenyl oxide/graphite cloth (parallel)

Figure 28. Specimens After Test ASD-13, Nozzle End Section.



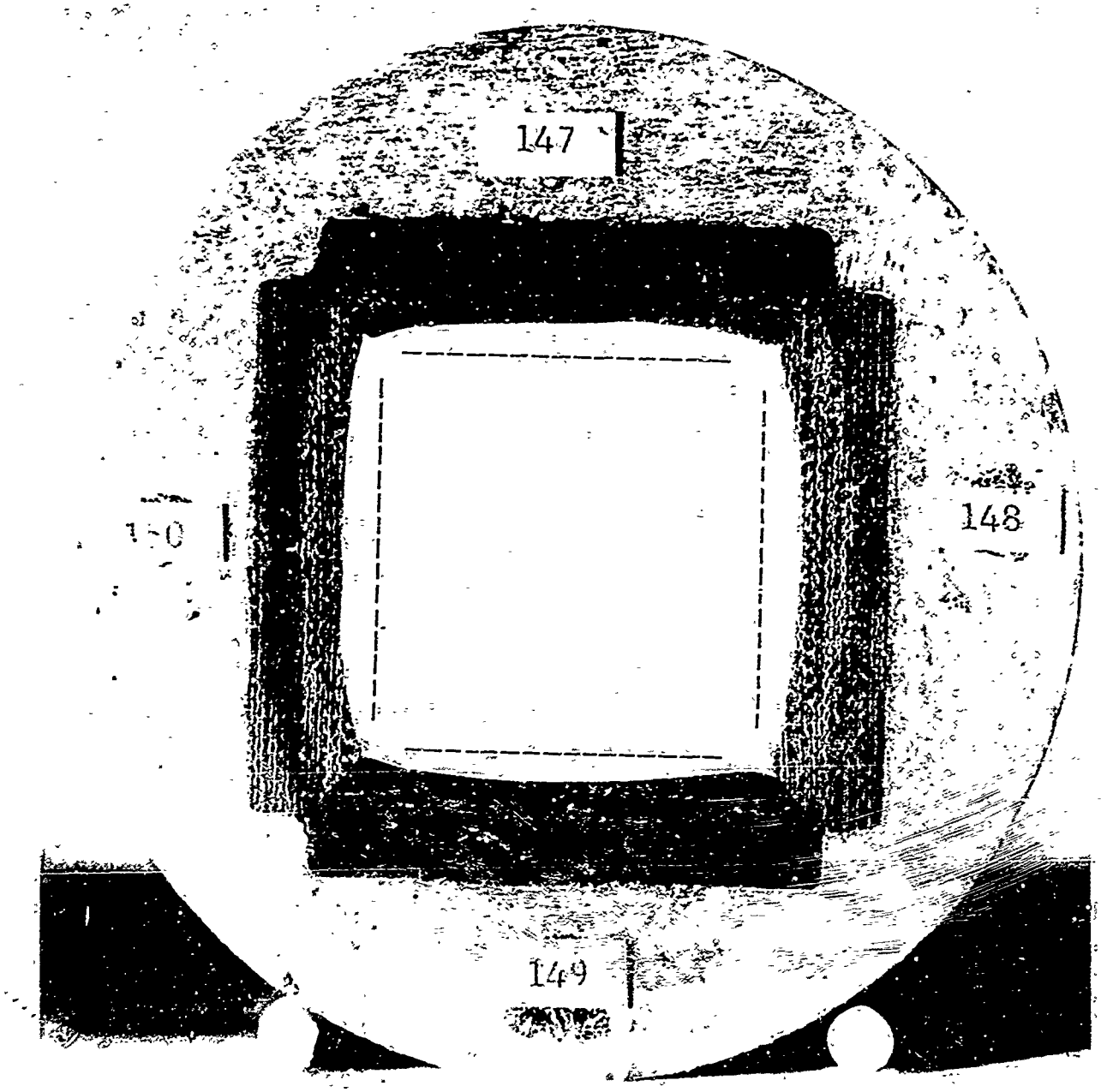
Phenolic/graphite cloth (parallel)

Figure 29. Specimens After Test ASD-13, Center Section.



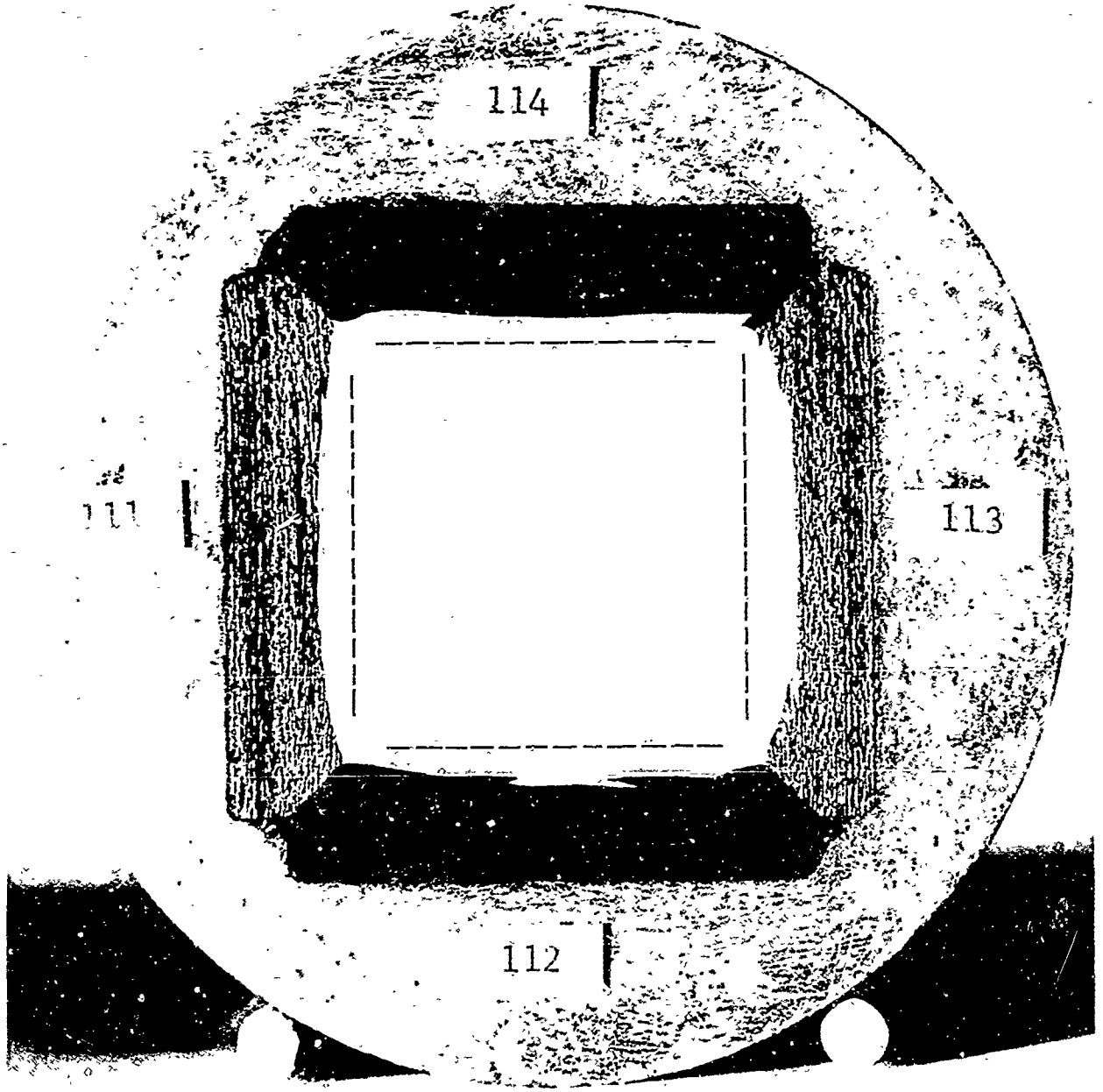
Chrome phenolic/graphite cloth (parallel)

Figure 30. Specimens After Test ASD-13, Motor End Section.



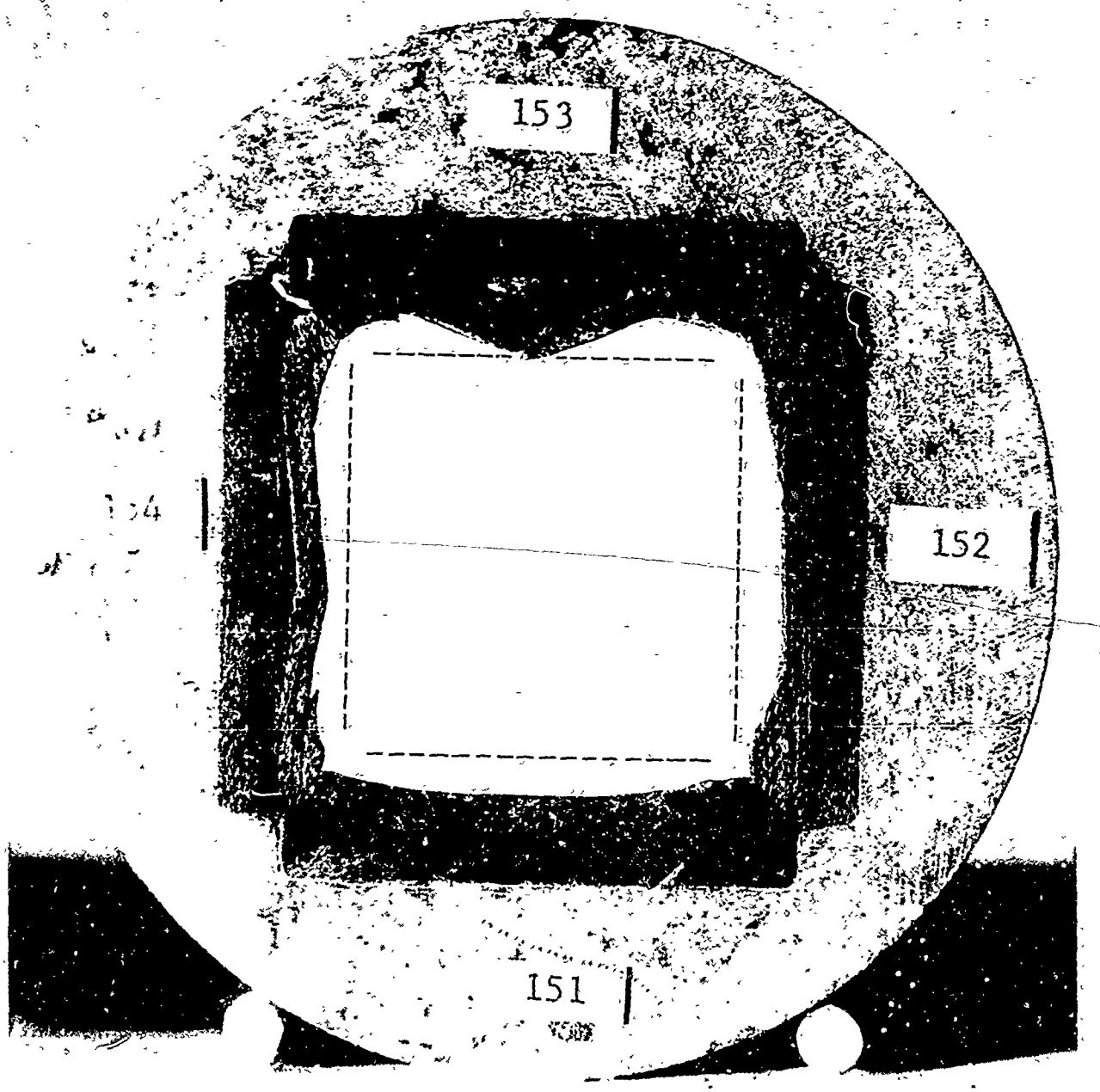
Phenolic/Pluton B-1 cloth (parallel)

Figure 31. Specimens After Test ASD-14, Nozzle End Section.



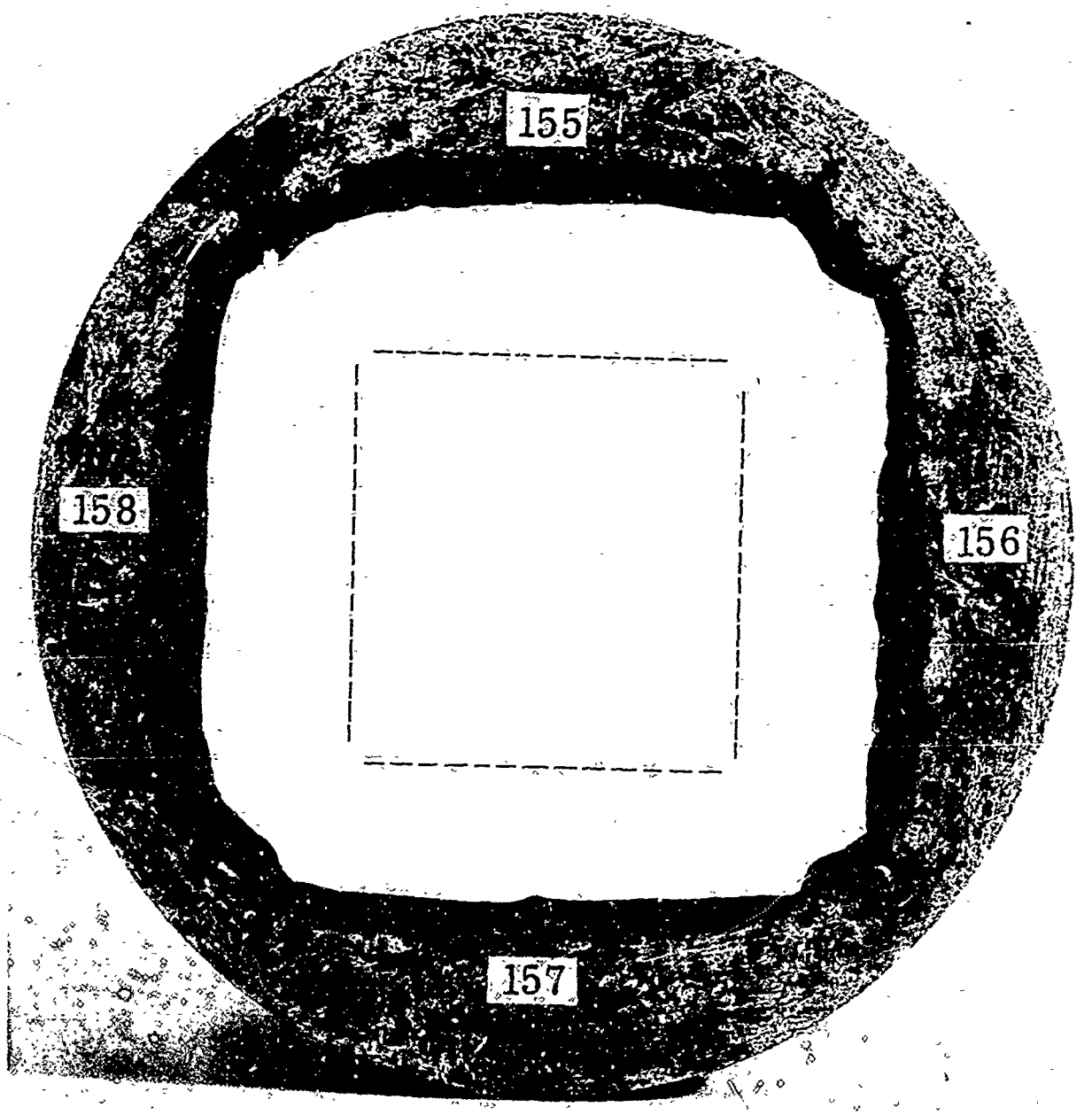
Phenolic/graphite cloth (parallel)

Figure 32. Specimens After Test ASD-14, Center Section.



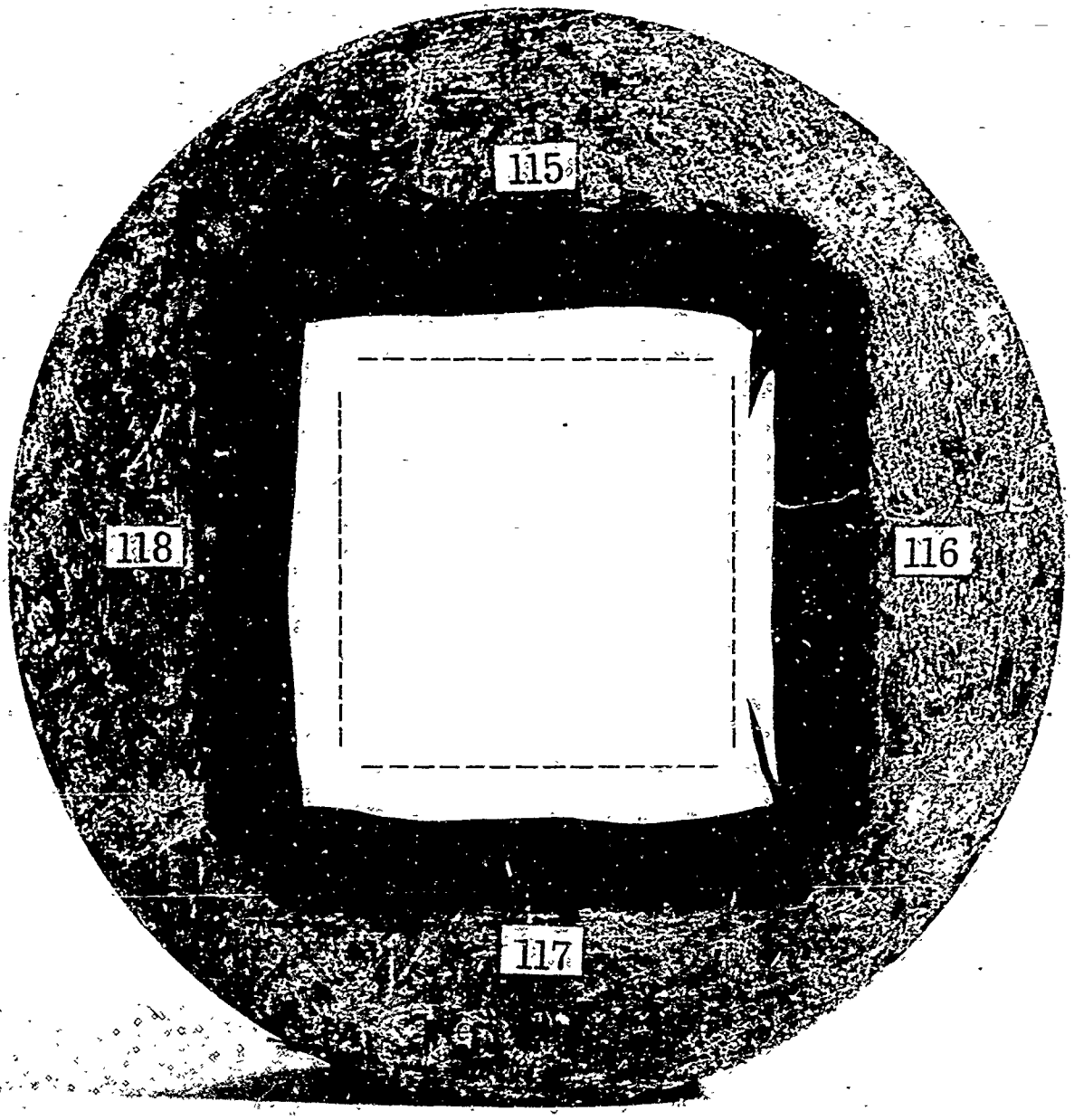
Phenolic/Pluton H-1 cloth (parallel)

Figure 33. Specimens After Test ASD-14, Motor End Section.



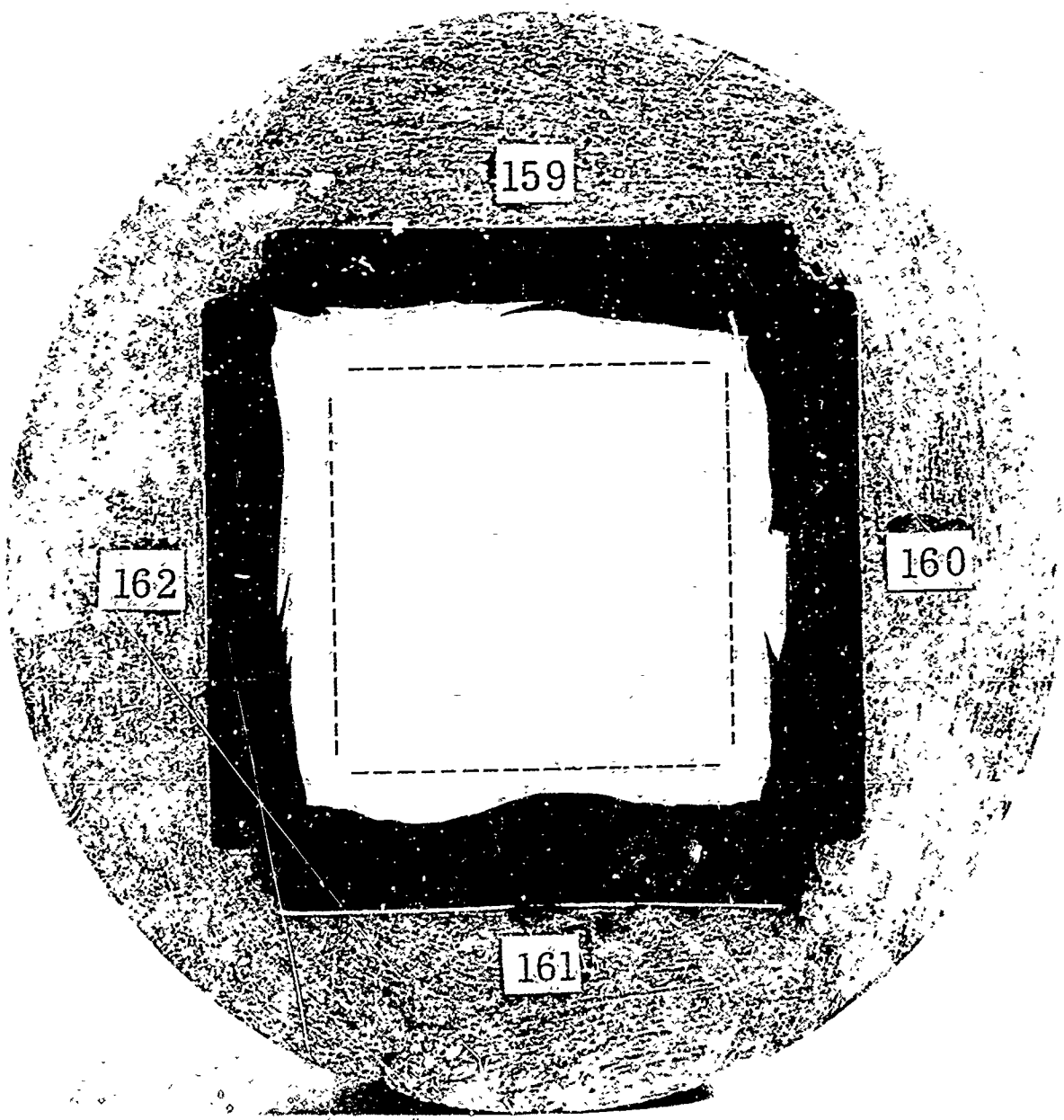
Polyphenylene oxide/graphite cloth (parallel)

Figure 34. Specimens After Test ASD-15, Nozzle End Section.



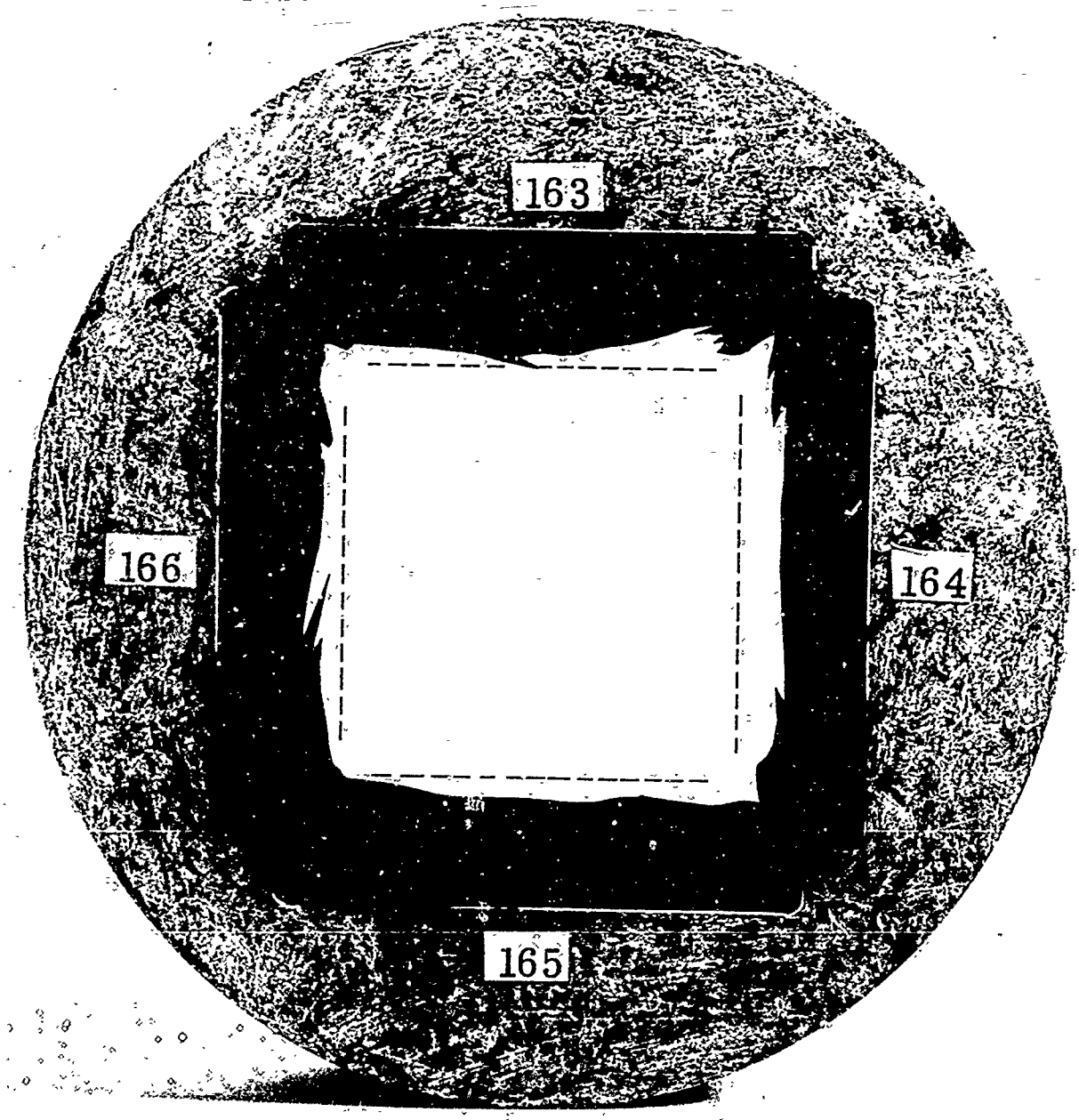
Phenolic/graphite cloth (parallel)

Figure 35. Specimens After Test ASD-15, Center Section.



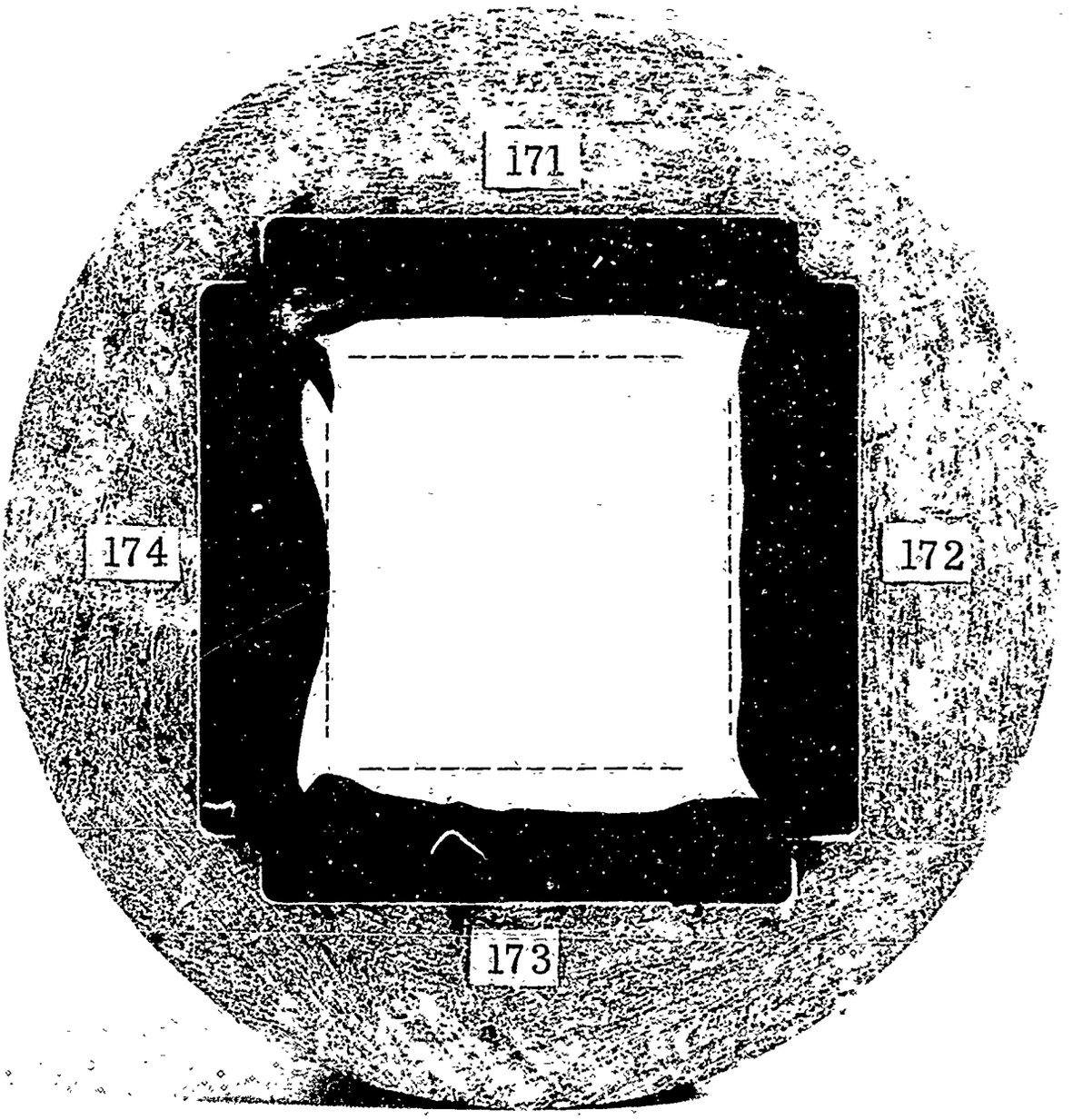
Tungsten-phenolic/graphite cloth (parallel)

Figure 36. Specimens After Test ASD-15, Motor End Section.



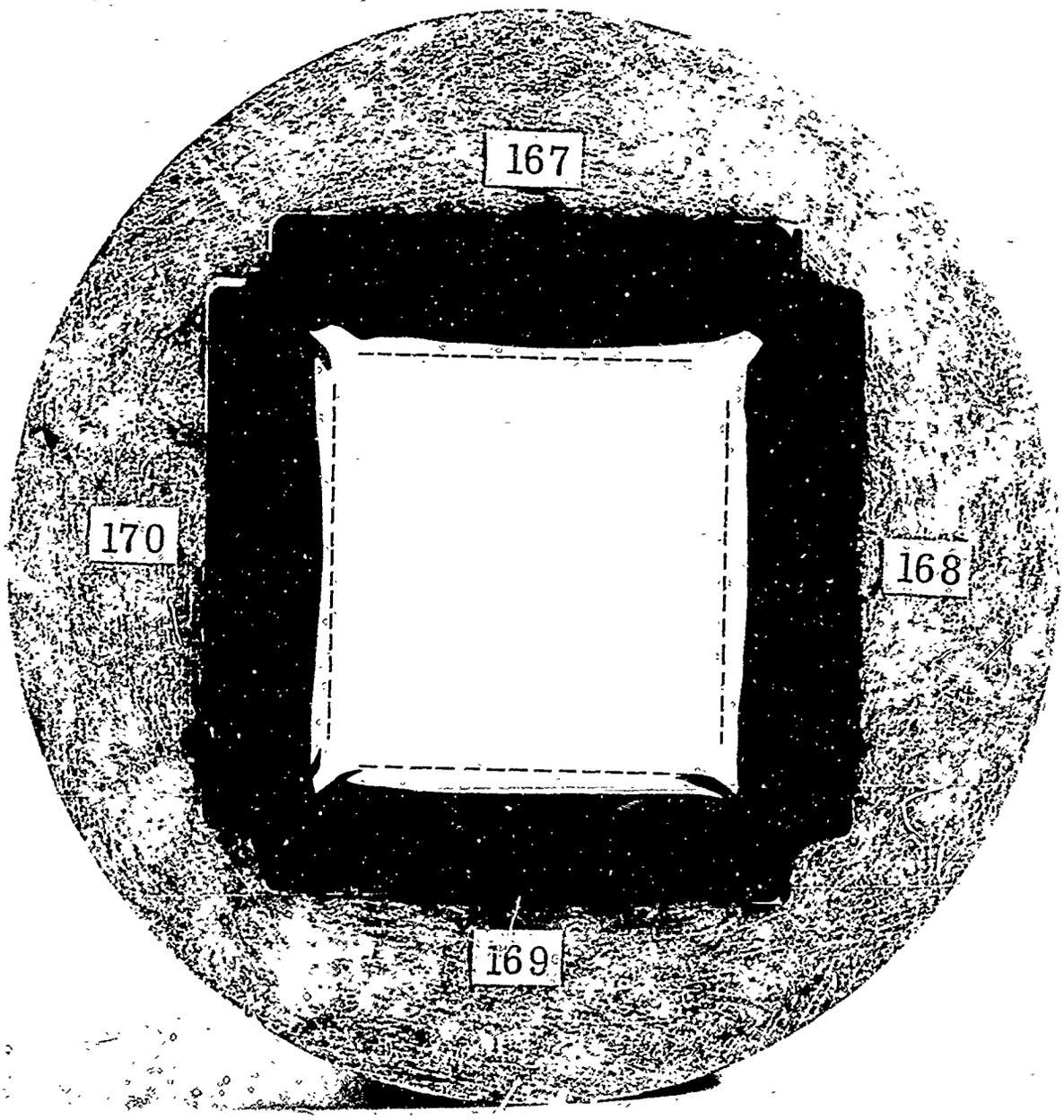
Polyphenyl/carbon cloth (parallel)

Figure 37. Specimens After Test ASD-16, Nozzle End Section.



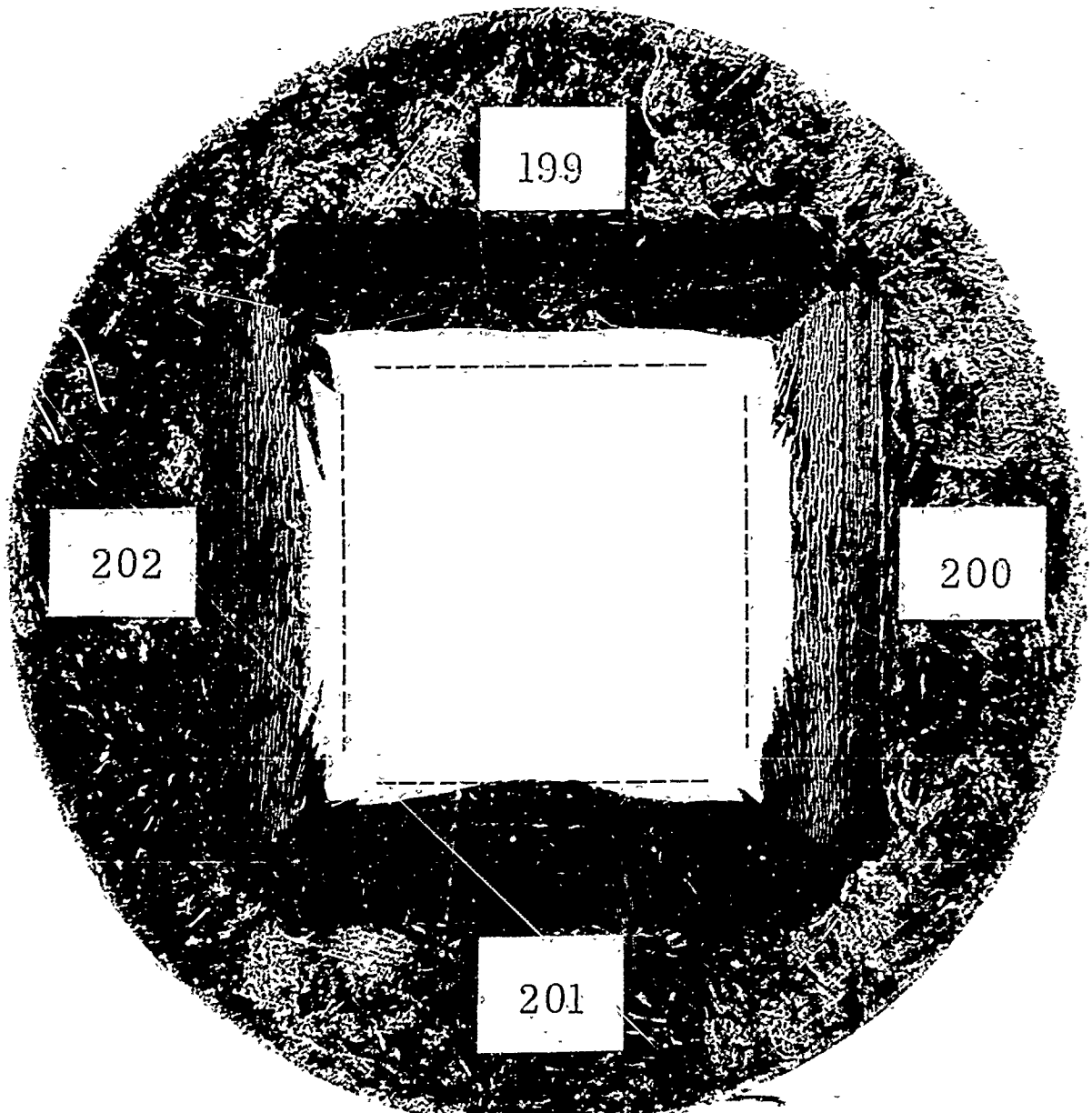
Phenolic/carbon cloth (parallel)

Figure 38. Specimens After Test ASD-16, Center Section.



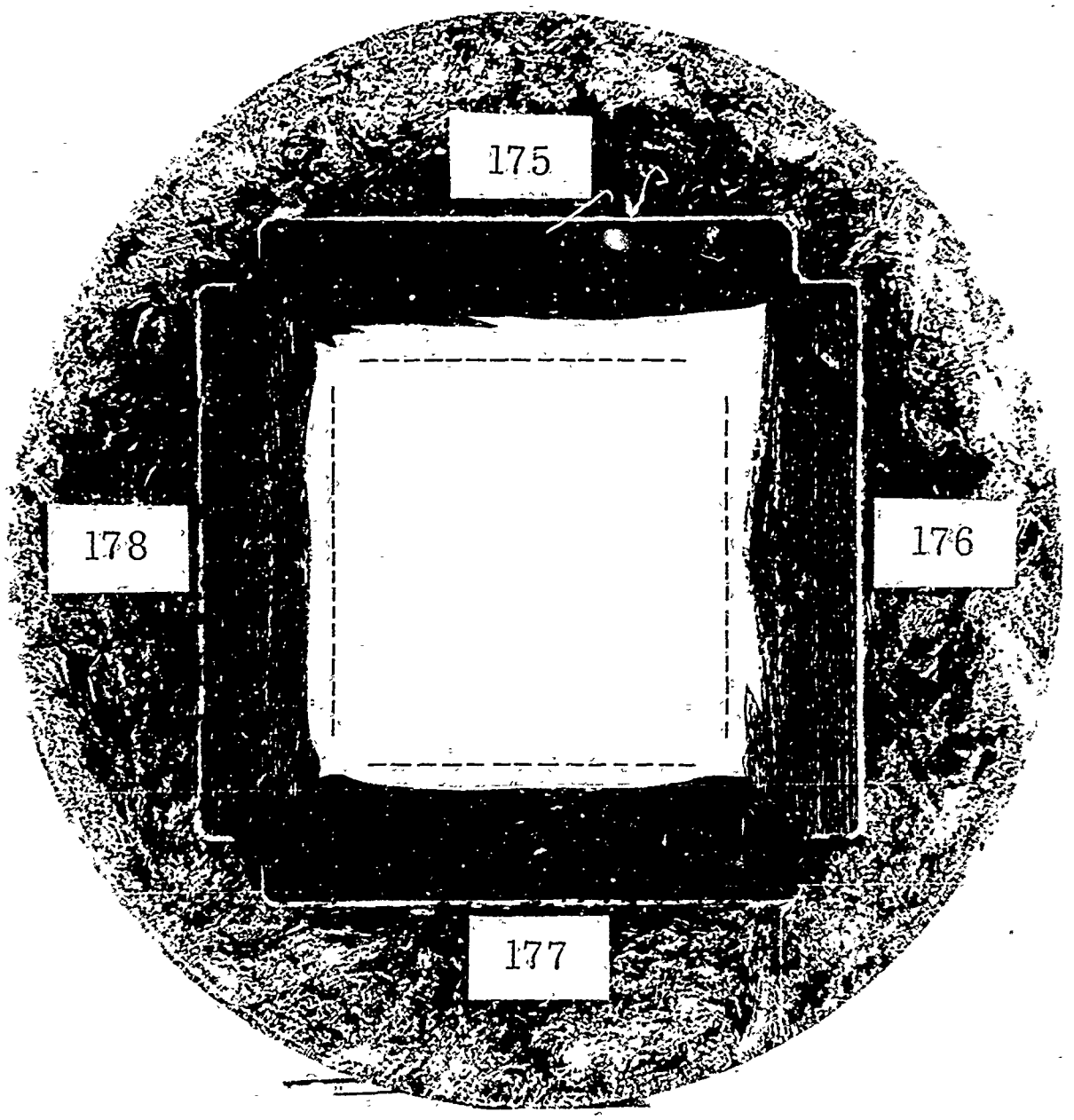
Naphthalene diol/carbon cloth (parallel)

Figure 39. Specimens After Test ASD-16, Motor End Section.



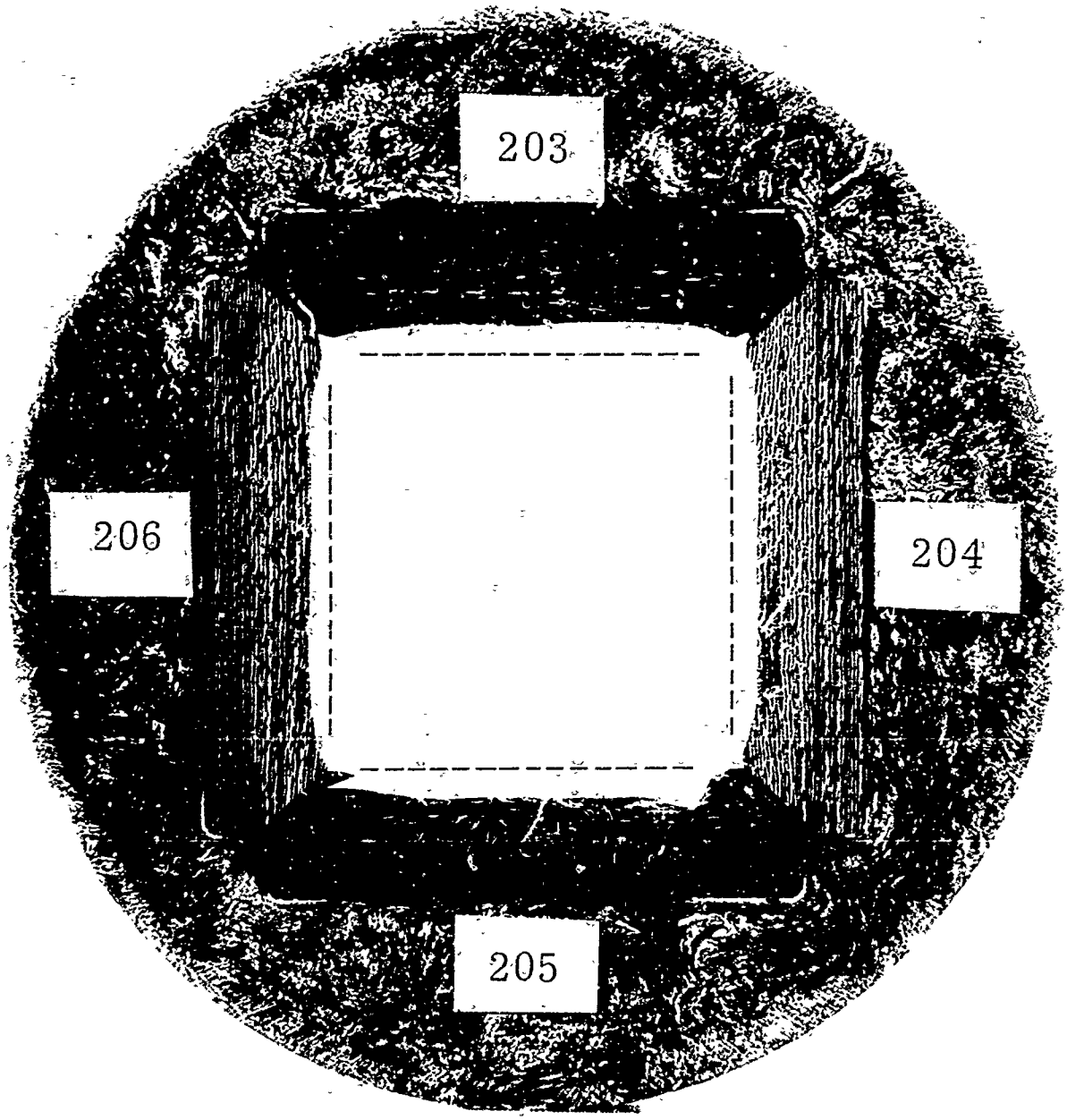
Polyphenylene/carbon cloth (parallel)

Figure 40. Specimens After Test ASD-17, Nozzle End Section.



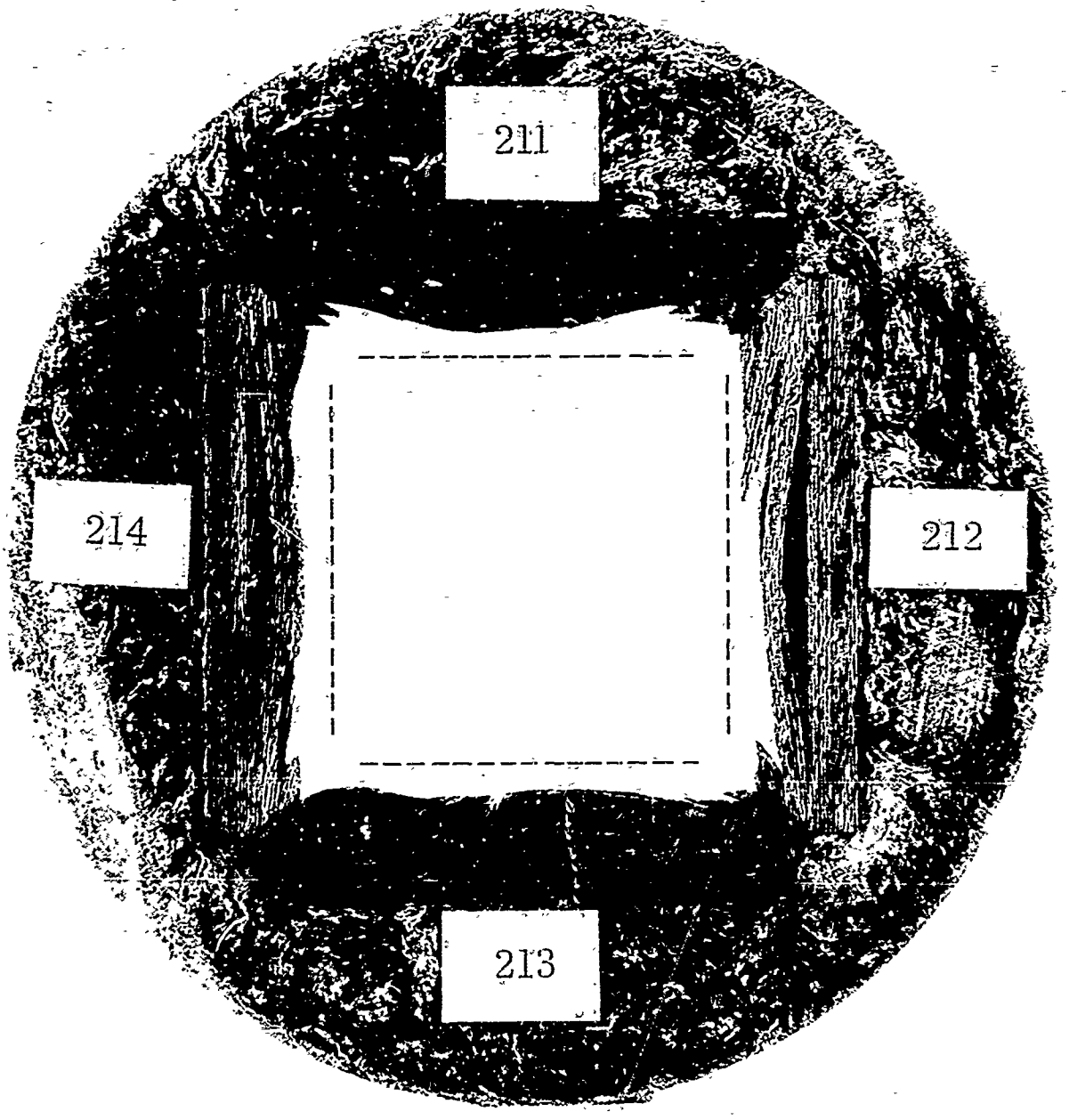
Phenolic/carbon cloth (parallel)

Figure 41. Specimens After Test ASD-17, Center Section.



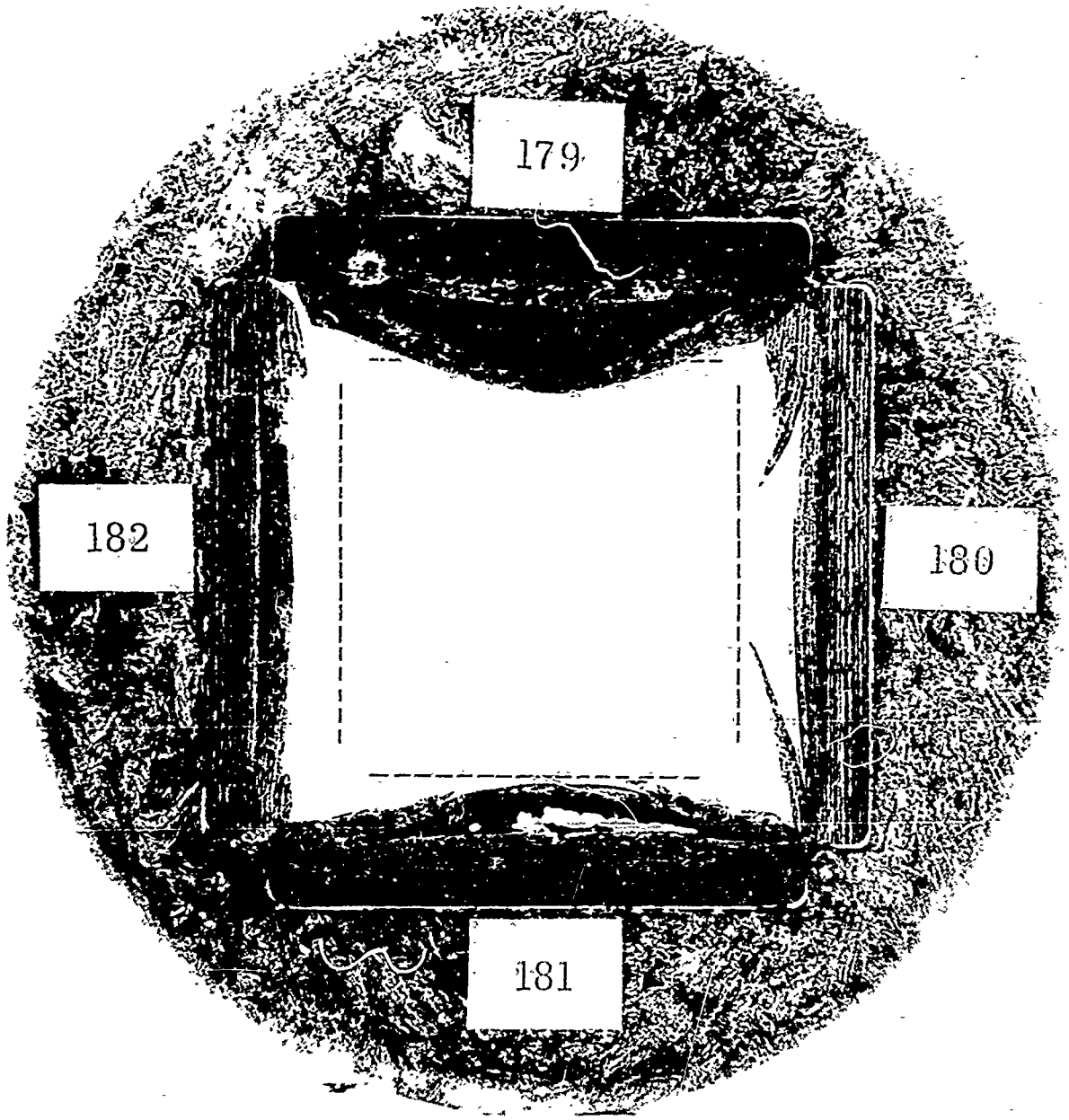
Polyimide/carbon cloth (parallel)

Figure 42. Specimens After Test ASD-17, Motor End Section.



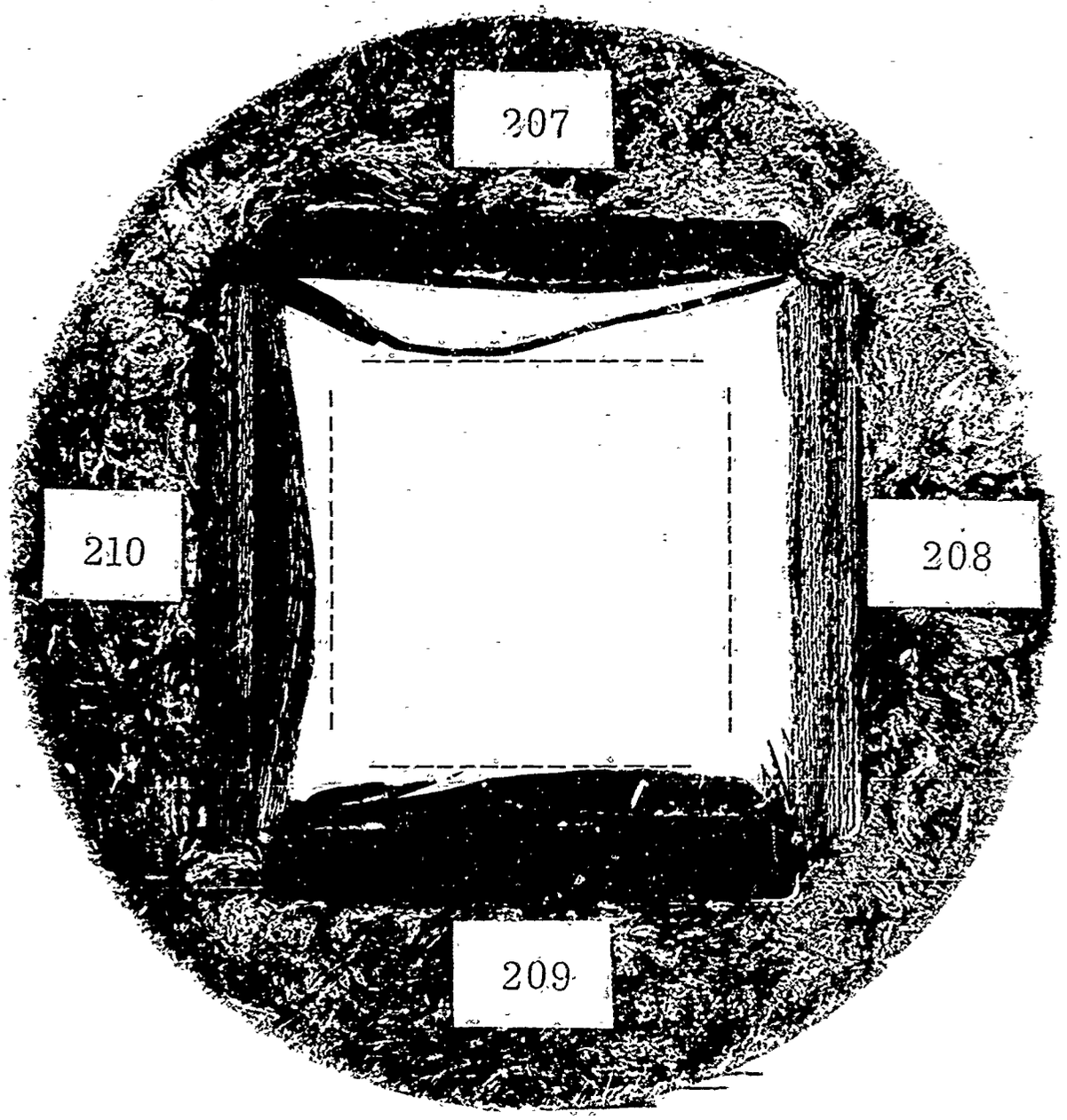
Polyphenylene phenolic/carbon cloth (parallel)

Figure 43. Specimens After Test ASD-18, Nozzle End Section.



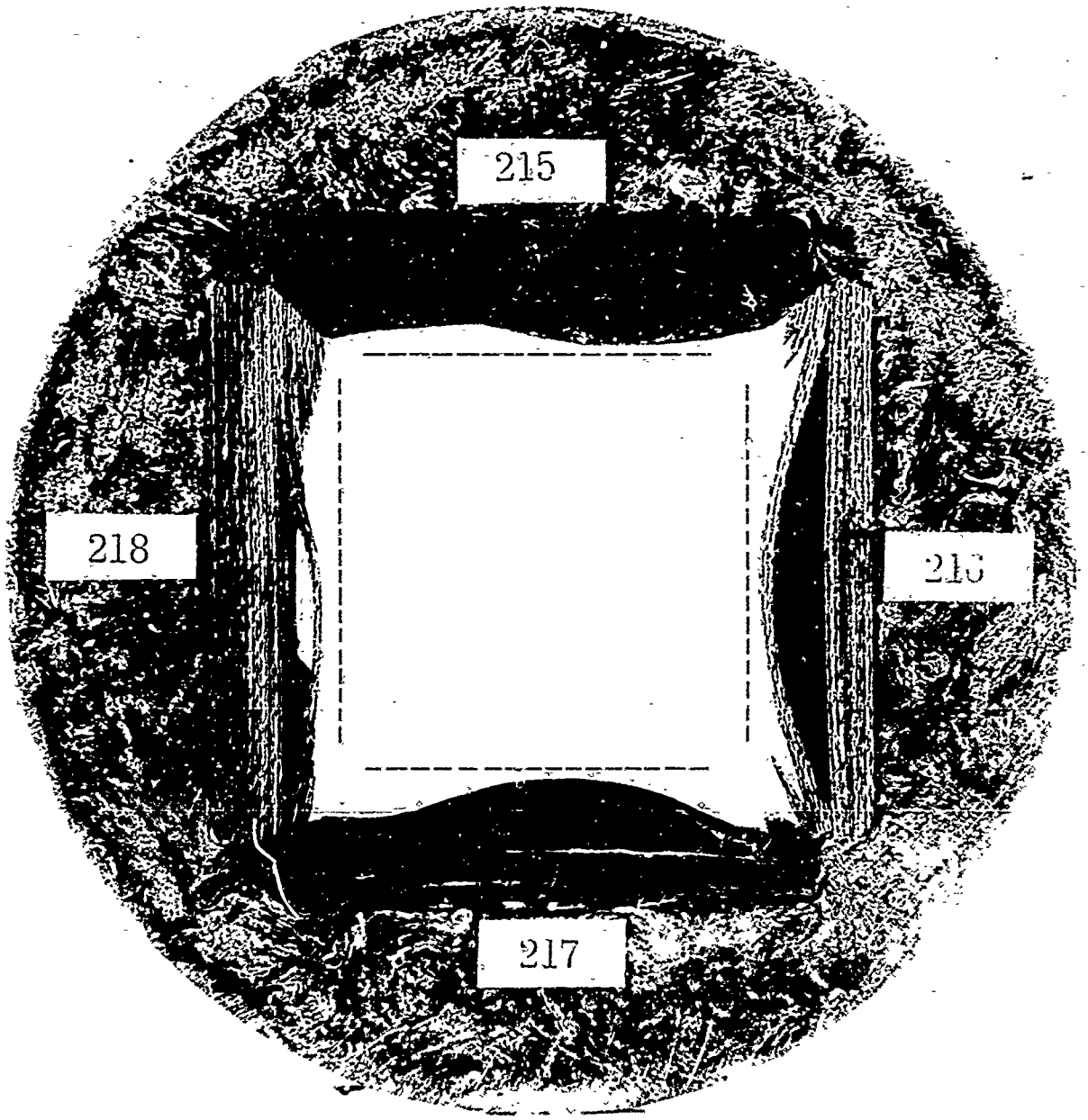
Phenolic/carbon cloth (parallel)

Figure 44. Specimens After Test ASD-18, Center Section.



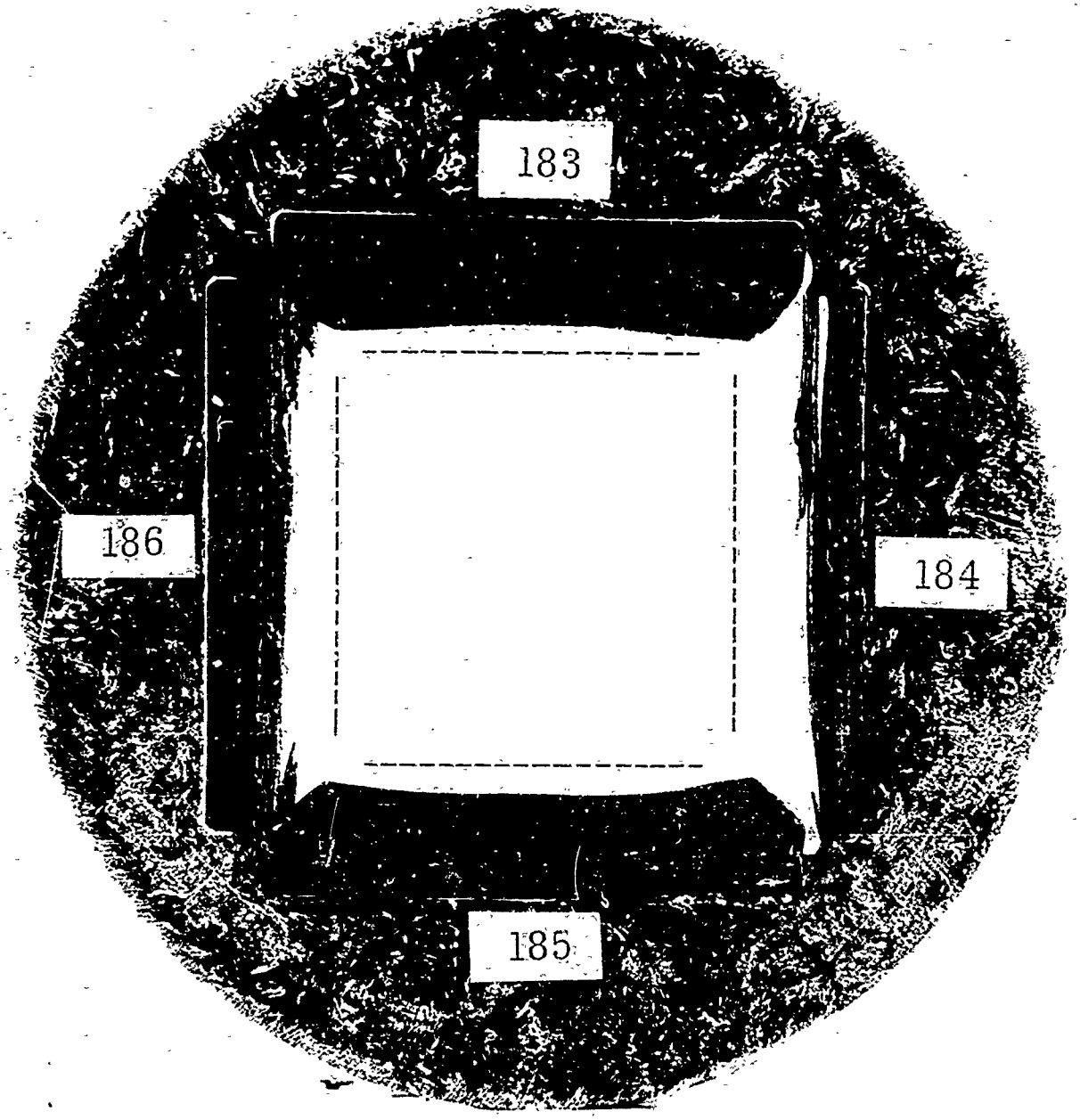
Polyarylene phenolic/carbon cloth (parallel)

Figure 45. Specimens After Test ASD-18, Motor End Section.



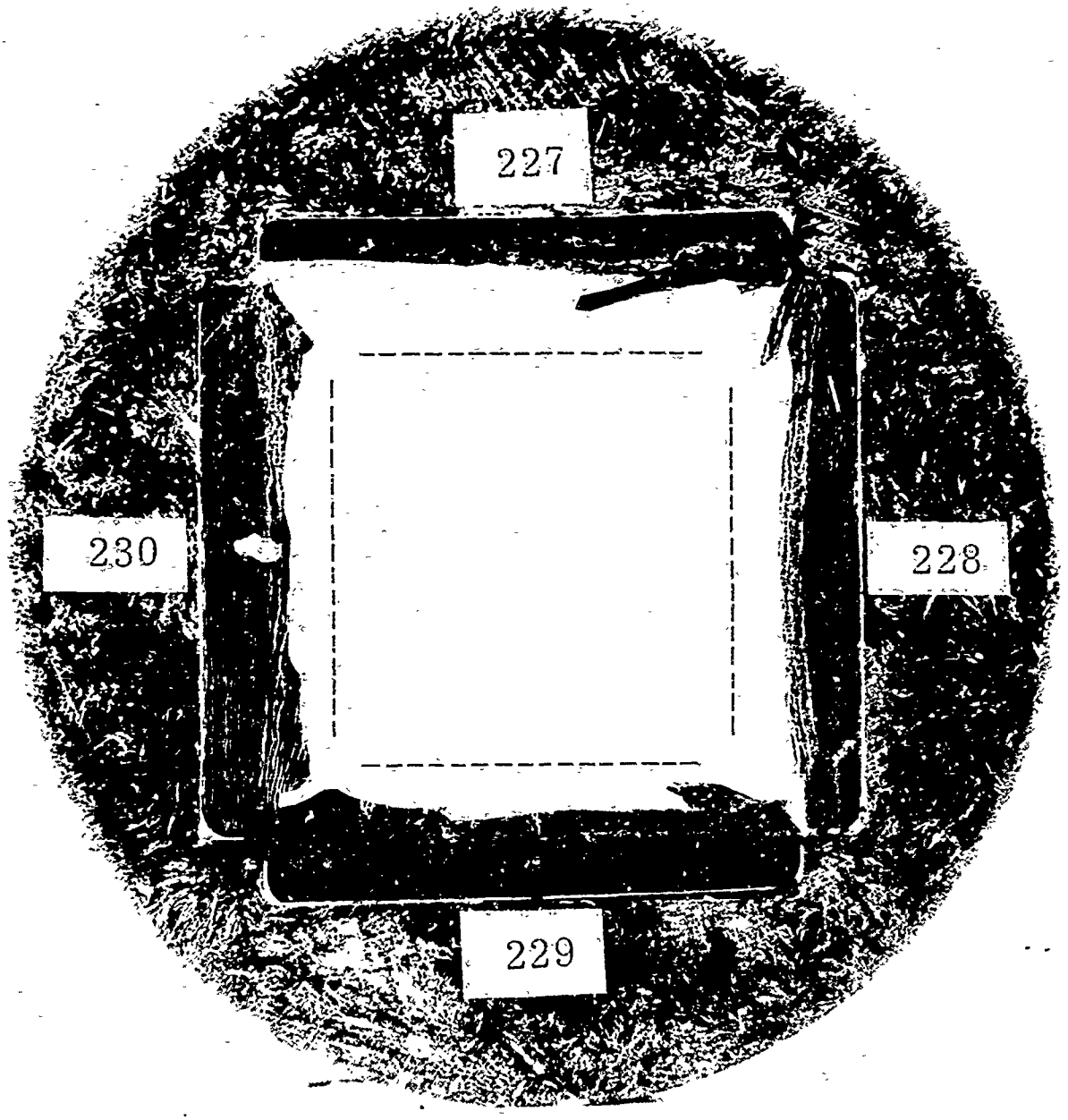
Phenyl aldehyde/carbon cloth (parallel)

Figure 46. Specimens After Test ASD-19, Nozzle End Section.



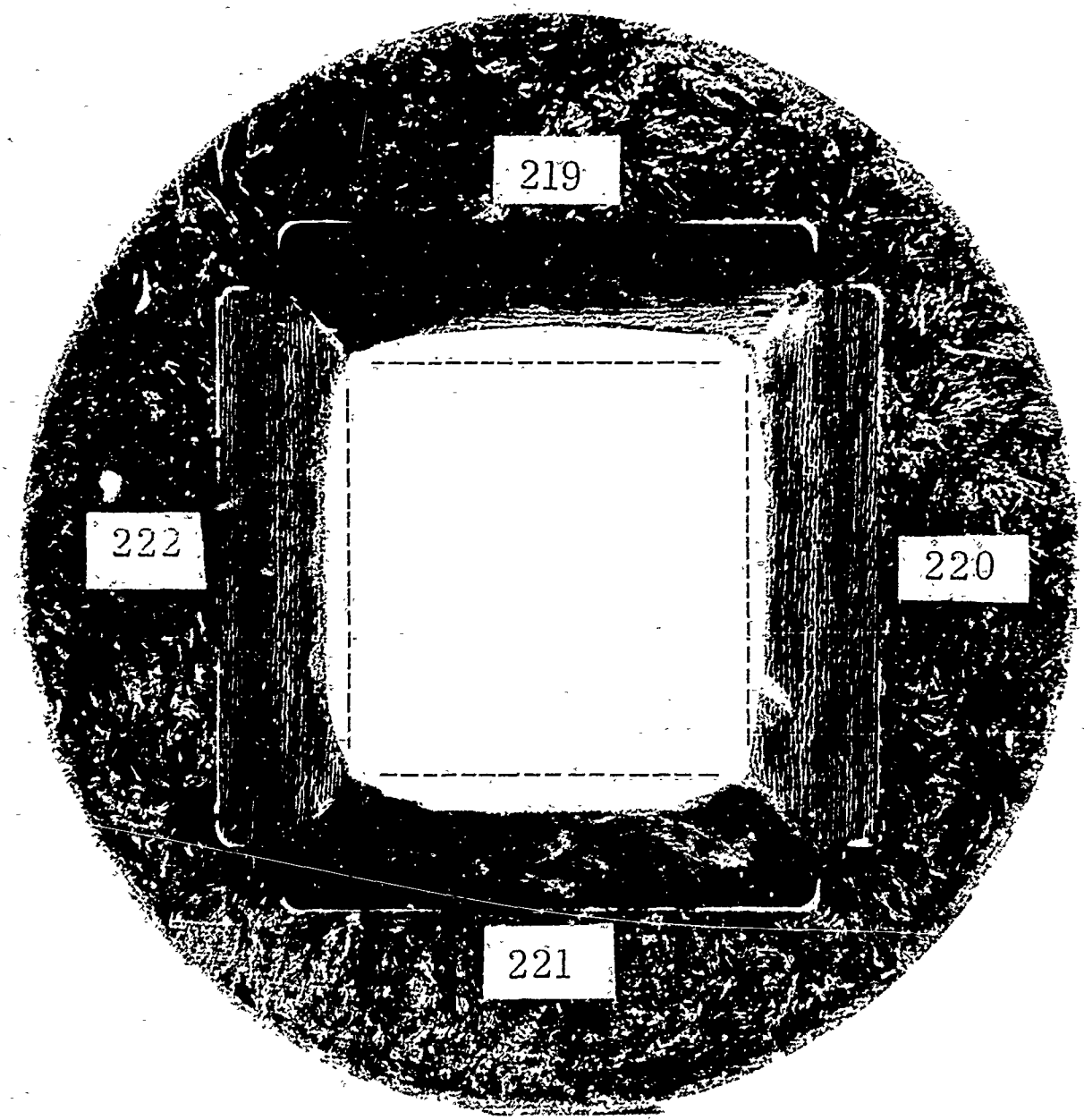
Phenolic/carbon cloth (parallel)

Figure 47. Specimens After Test ASD-19, Center Section.



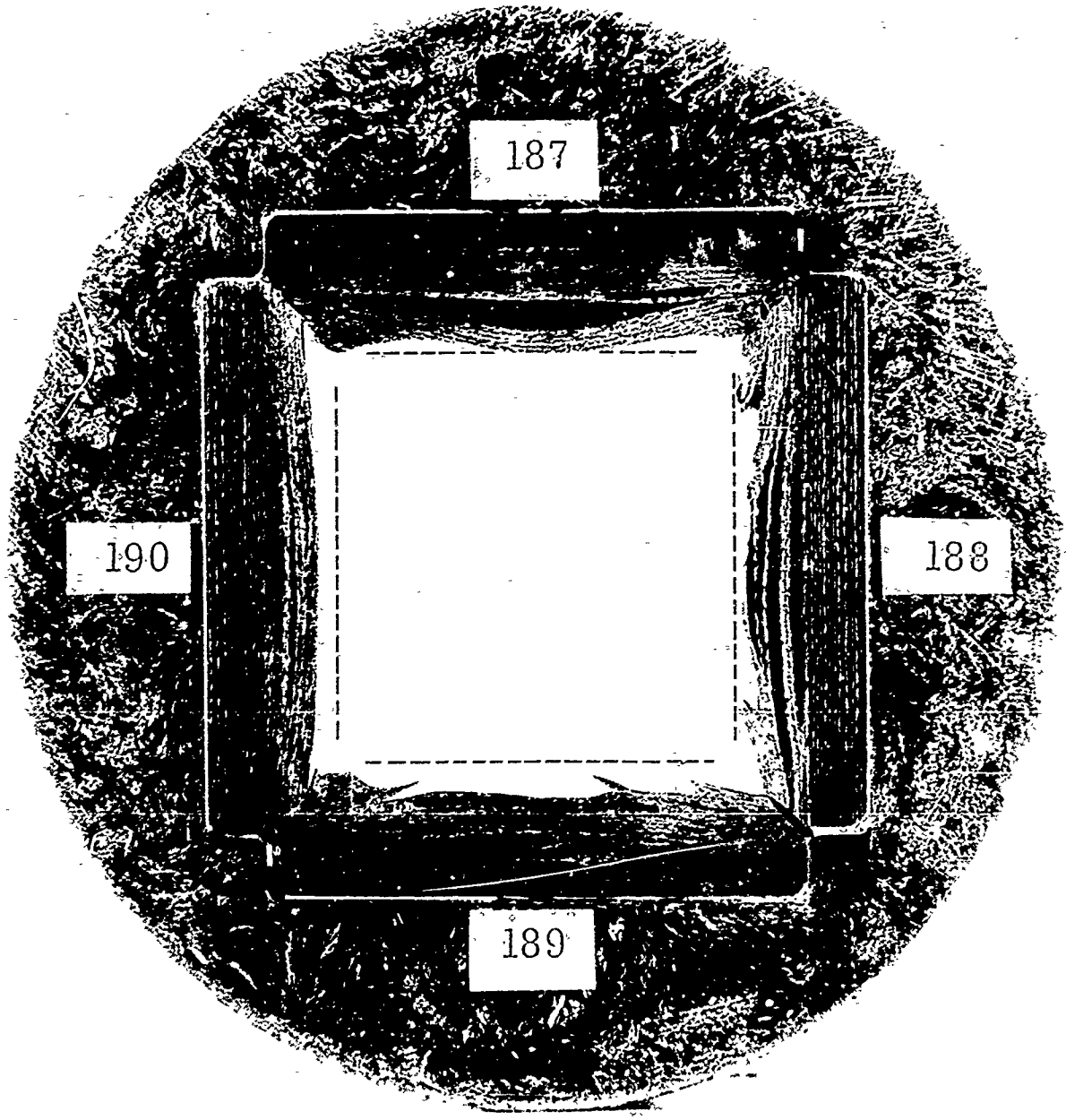
Epoxy/polyphenylene(intractable)/carbon cloth (parallel)

Figure 48. Specimens After Test ASD-19, Motor End Section.



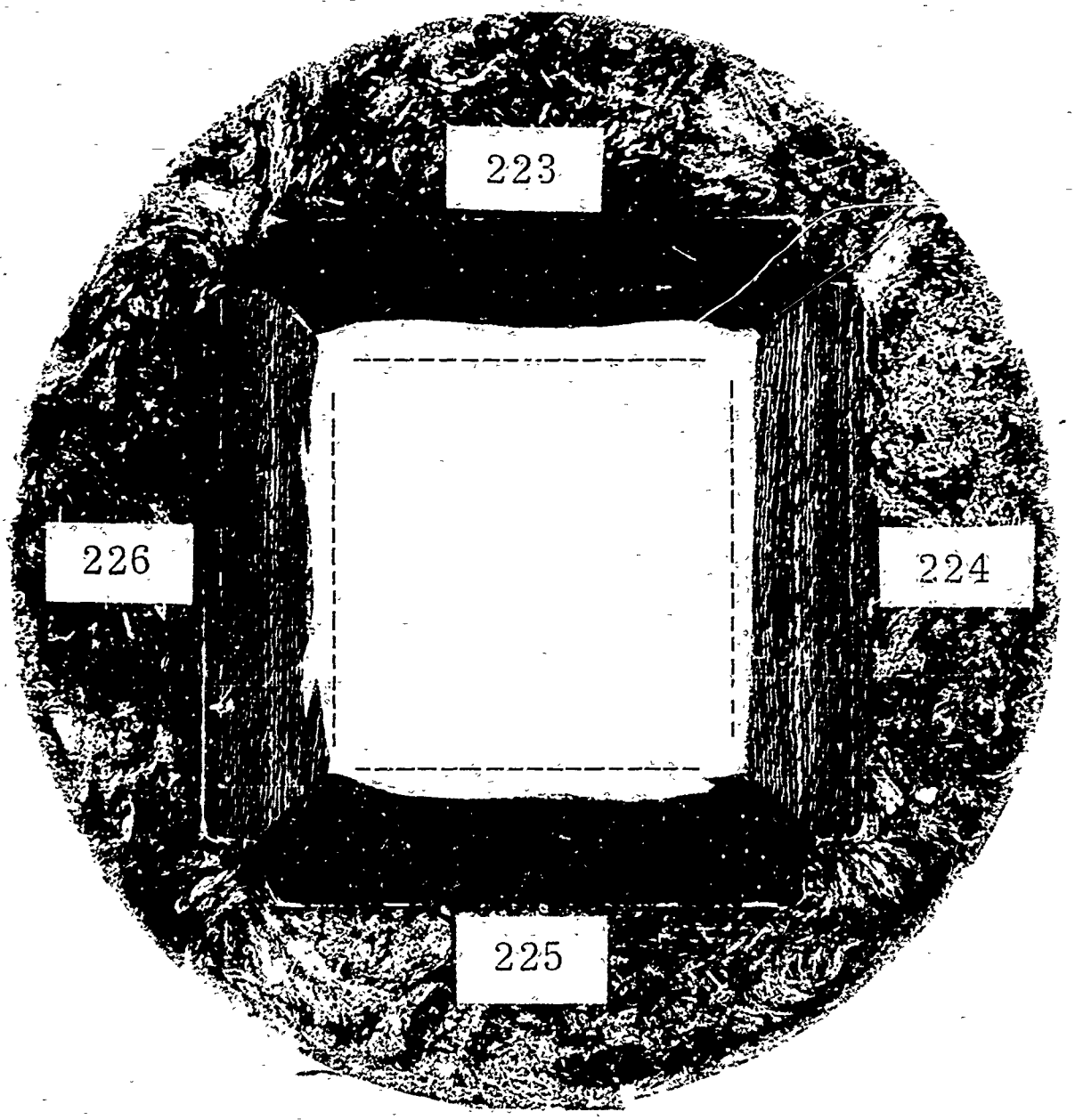
Phenolic/polyphenylene(intractable)/carbon cloth (parallel)

Figure 49. Specimens After Test ASD-20, Nozzle End Section.



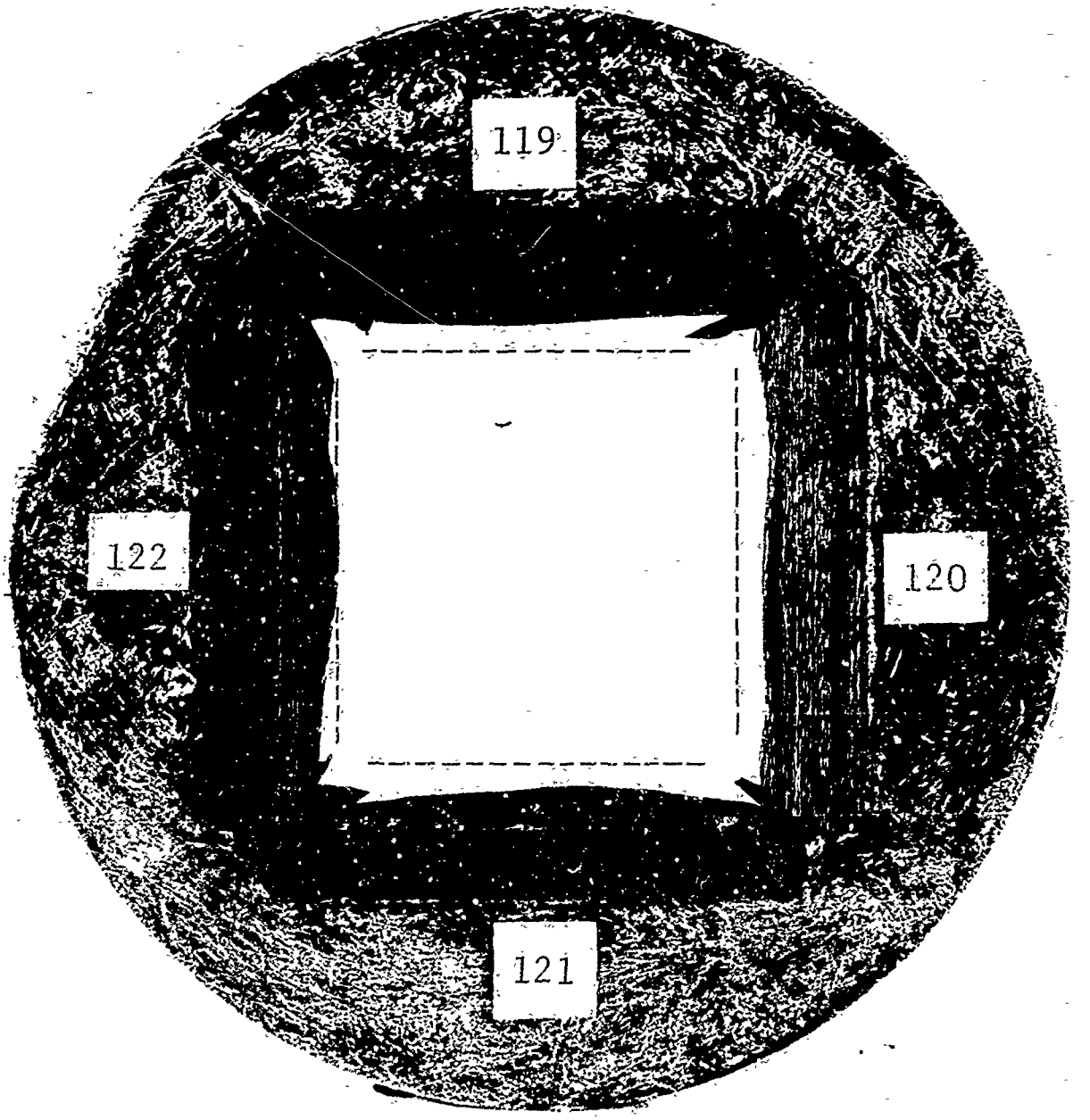
Phenolic/carbon cloth (parallel)

Figure 50. Specimens After Test ASD-20, Center Section.



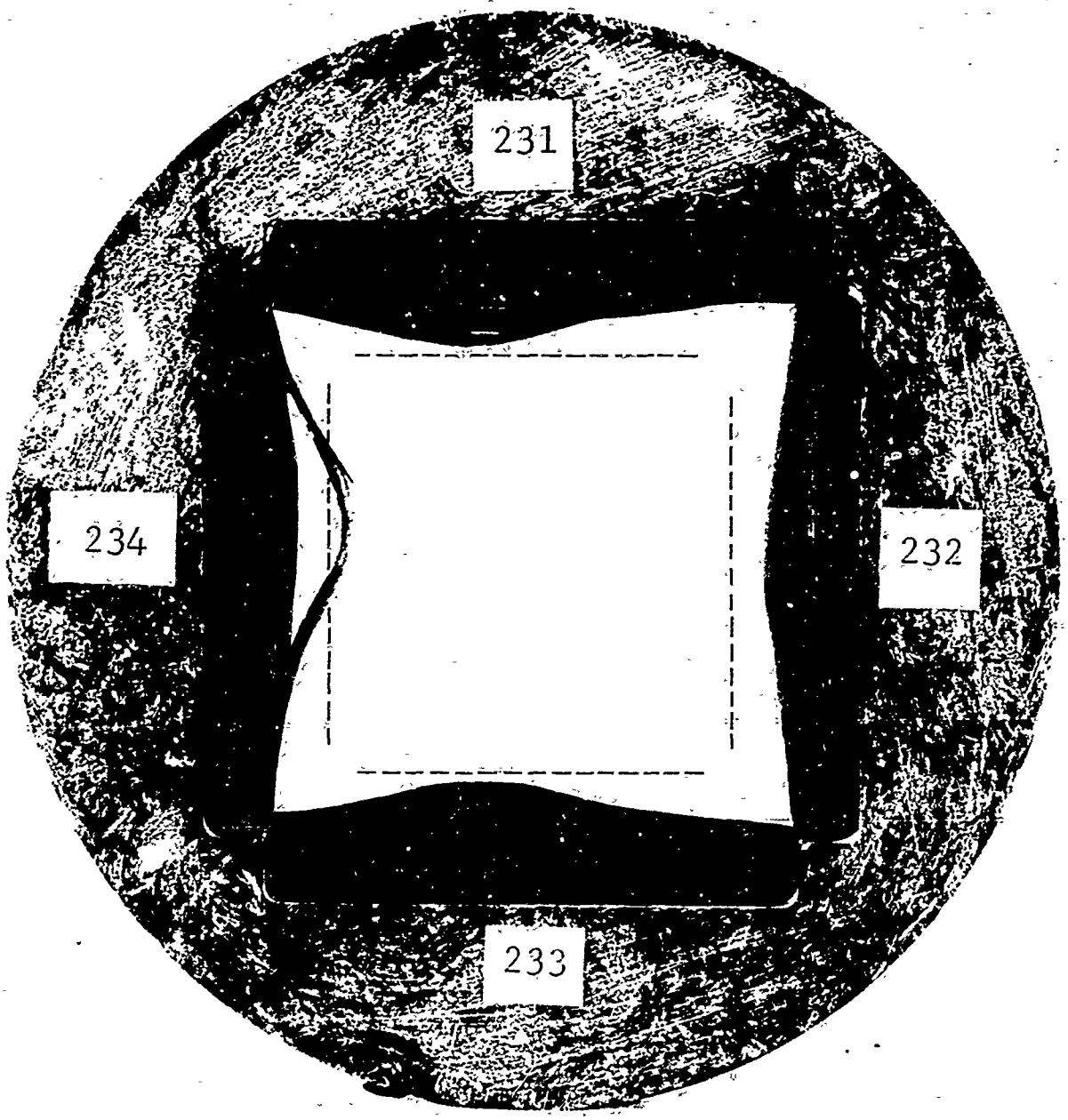
p-phenylphenol phenol formaldehyde/
polyphenylene(intractable)/carbon cloth (parallel)

Figure 51. Specimens After Test ASD-20, Motor End Section.



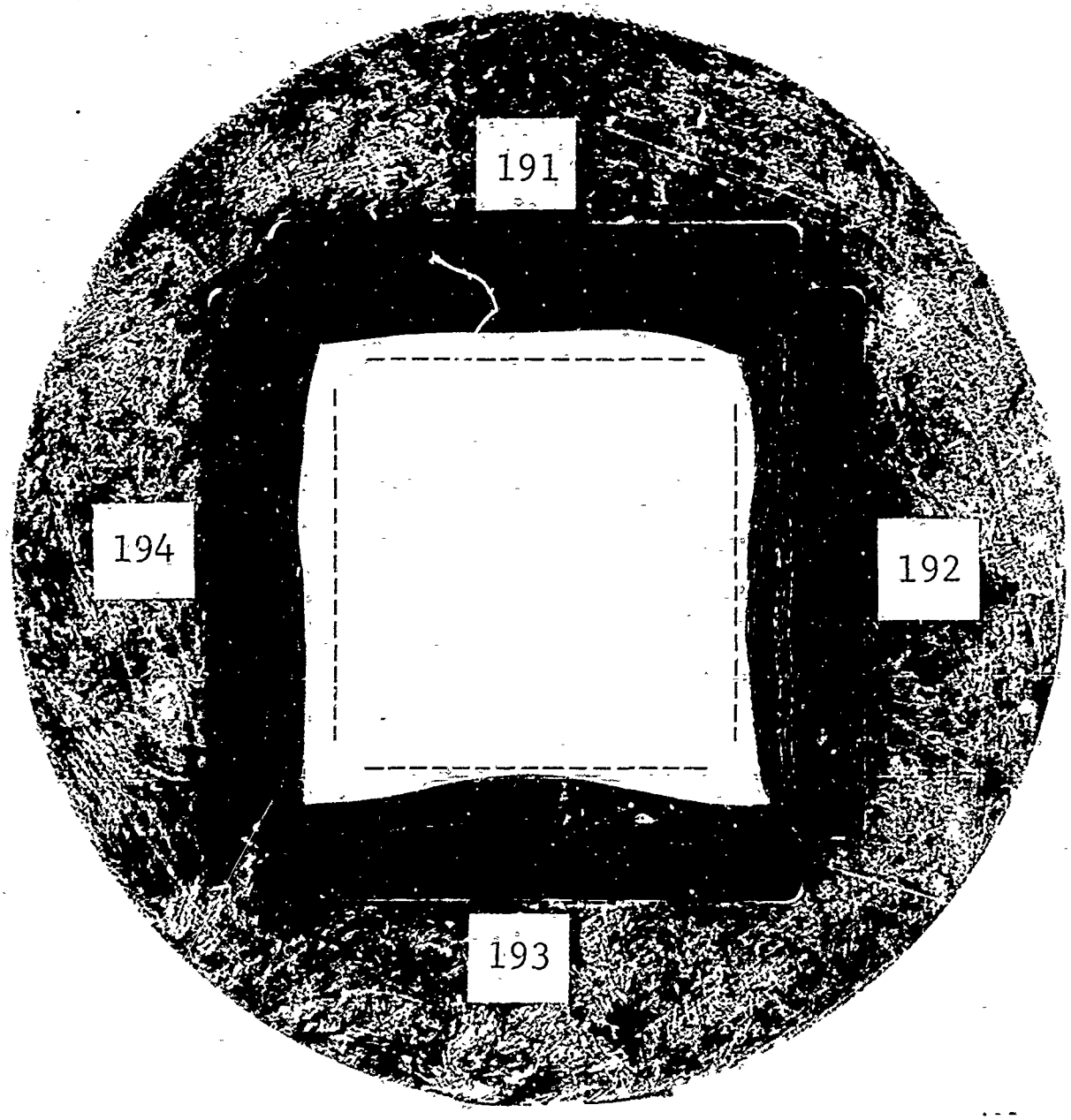
Phenolic/graphite cloth (parallel)

Figure 52. Specimens After Test ASD-21, Nozzle End Section.



Biphenol formaldehyde/carbon cloth (parallel)

Figure 53. Specimens After Test ASD-21, Center Section.



Phenolic/carbon cloth (parallel)

Figure 54. Specimens After Test ASD-21, Motor End Section.

Specimen No. 227

Specimen No. 228

Figure 55. Delaminations Noted in Specimens Prior to Test.

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5. AUTHOR(S) (Last name, first name, initial)

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13. ABSTRACT The purpose of this program was to characterize ablative plastics for service in the nozzle region of solid propellant motors. Evaluation of specimens provided by the Air Force Materials Laboratory was accomplished by exposure to a realistic chemical, mechanical, and thermal environment in a subscale, high-velocity motor test. This report describes the work of the final nineteen months of a thirty-two month program. The standard test method developed in the previous year (AFML TR 65-315) was used for thirteen firing tests. Based on the first two of these firings, flat laminate specimens were chosen as standard because char rate data could be obtained and specimen fabrication was greatly simplified. In the final eleven firing tests, seventeen different resins or resin mixtures were compared with a standard commercial phenolic with either graphite or carbon cloth reinforcement. Two resins (naphthalene diol and phenylphenol phenol formaldehyde) gave significantly better results than the standard. Several other resins, including a chrome phenolic polyphenyl, polyimide, and 2-7 dihydroxynaphthalene phenol formaldehyde, showed either similar performance or promise for improved performance.

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